

# **Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change**

## **Economic Evaluation of Carbon Dioxide and Nitrous Oxide Emission Reductions in Industry in the EU**

### **Bottom-up Analysis**

Final Report  
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Jeroen de Beer and Dian Phylipsen  
Ecofys, P.O. Box 8408  
NL-3503 RK Utrecht

Judith Bates  
AEA Technology Environment  
E6 Culham, Abingdon  
OX14 3ED, UK

Contact: Chris Hendriks  
[c.hendriks@ecofys.nl](mailto:c.hendriks@ecofys.nl)

<http://europa.eu.int/comm/environment/enveco>

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National Technical University of Athens**

## **Preface**

On its way to its current form this report has received significant input from a considerable number of experts. In particular, a panel of experts in Brussels discussed a draft version of the report on March 29 and 30, 2000 (see Annex 2 for a list of names), and made a number of specific and more general comments and suggestions. Also after the workshop many experts and industry organisations - such as Ceramunie, CEPI, CEFIC, Eurofer, Europia, EISI, CPIU and others - gave the comments on the adapted version of the report. The authors would like to thank all these people for their valuable inputs into this study. For this report it was attempted to consider their suggestions wherever possible in the text. However, due to time constraints it was not always possible to discuss all comments made after the expert panel in March in the text. Specific comments are therefore added in footnotes to show the view of the experts on the information provided in this report.

## EXECUTIVE SUMMARY

Within the EU, industrial activity is an important source of carbon dioxide, accounting for 40% of total direct and indirect carbon dioxide emissions in 1990 and 30% of total greenhouse gas emissions. Greenhouse gases other than CO<sub>2</sub> contribute for about 5% to total greenhouse gases emitted in this sector.

Indirect emissions (emissions from steam and electricity production) in this sector play an important role. Emission from energy supply that can be allocated to industry contributes to about 60% of the total emissions in this sector.

### Description of the sector

In the sector industry 9 subsectors are distinguished: iron and steel, non-ferrous metals, chemicals, building materials, paper and pulp, food drink & tobacco, engineering, textiles, and others.

### Frozen technology reference level

The emission reduction potential for 2010 is calculated using an emission reference level based on frozen technology development, assuming that no energy improvement is obtained and that no reduction of specific energy consumption occurs. In the frozen technology reference level greenhouse gas emissions of the industrial sector are about 35% higher (1495 Mt in 1990 compared to about 2007 Mt of CO<sub>2</sub> equivalent in 2010). Table 1 gives an overview of the emission levels of CO<sub>2</sub> for the subsectors.

*Table 1. 1990 energy use, and direct (including process emission) and indirect emission (steam and electricity consumption related) of CO<sub>2</sub> (in Mt CO<sub>2</sub>), and 2010 frozen technology reference level (2), thus excluding effects by efficiency improvements, fuel shift and intrasubsectoral product shifts. Fuel use, emissions and projections on industrial production grow rates are taken from Primes [1999]. Figures in italics refer to own estimate.*

(Sub)sector	1990 Fuel use	Direct CO <sub>2</sub> emission	Indirect CO <sub>2</sub> emission	1990 total CO <sub>2</sub> emissions	2010 frozen technology reference level
	EJ	Mt	Mt	Mt	Mt
Iron and Steel	2.3	198	48	246	266
Non-ferrous metals	0.5	16	33	50	68
Chemicals	2.0	38	217	254	420
Building materials	1.5	204	28	232	276
Paper, pulp and printing	1.0	10	124	135	218
Food, drink, tobacco	0.9	11	96	107	166
Others	1.0	104	160	264	374
<b>Total</b>	<b>9.3</b>	<b>581</b>	<b>706</b>	<b>1287</b>	<b>1789</b>

All emission data refer to CO<sub>2</sub> only. Inclusion of non-CO<sub>2</sub> greenhouse emissions increase total greenhouse gas emissions by 16% for 1990 and 12% for 2010 frozen technology reference level.

Besides emission of CO<sub>2</sub> a number of industrial activities cause emissions of other greenhouse gases like nitrous oxide and fluorinated gases, and to a lesser extent methane.

## Emission reduction options

In this study emission reduction options are identified to reduce emissions of industrial carbon dioxide, to reduce nitrous oxide emissions from the nitric acid and adipic acid manufacture and to reduce emissions from fluorinated gases.<sup>1</sup>

In this study the potentials for energy efficiency improvement are determined at the level of industrial subsectors. Only emission reduction options are included that have a high probability of being commercially available before 2010. Options regarding implementation of new capacity are defined based on technology with an efficiency level equal to the best practice value of 1995. In many cases a shift to another product mix (e.g. primary steel to secondary steel) might entail the potential to reduce emissions further. However, these intra-industrial structural changes are not considered in this bottom-up study.

Table 3 gives an overview of the investment costs, the yearly costs (sum of operation and maintenance costs and savings), average specific mitigation costs and potential for options applicable in the industry sector. The specific costs are calculated using a real interest rate of 4% and using the lifetime of the option, i.e. equipment. The technical reduction potential of all greenhouse gases is estimated at about 533 Mt of CO<sub>2</sub> equivalent. Including the technical emission reduction potential of the energy supply sector the reduction amounts to 1000 Mt of CO<sub>2</sub> equivalent or about 50% of total direct and indirect industrial emissions.

## Summary

Table 2 summarises the frozen technology reference level in the industry and shows the position if all the options in the table above were adopted.

Table 2. Summary of total direct and indirect emissions in industry (Mt CO<sub>2</sub> equivalent).

	1990	2010 frozen technology reference level	2010 with all options
<i>Carbon dioxide</i>	1287	1789	905
<i>Methane</i>	3	3	3
<i>Nitrous oxide</i>	143	135	47
<i>Fluorinated gases</i>	63	81	31
<b>Total</b>	<b>1495</b>	<b>2007</b>	<b>985</b>

<sup>1</sup> The options to reduce emission of fluorinated gases are not described in this report but in the report "Economic Evaluation of Emission Reductions of HFCs, PFCs and SF<sub>6</sub> in Europe", J. Harnisch and C. Hendriks, Ecofys, March 2000.

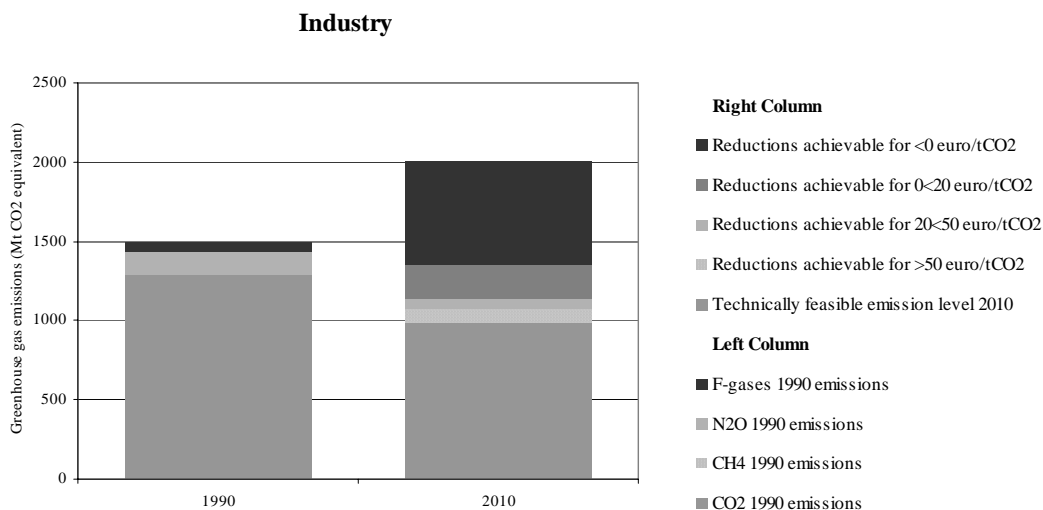
Figure 1 shows the share in emission reduction categorised in four cost brackets.

Table 3. EU15-average costs and total potential (Mt of CO<sub>2</sub> equivalent) for industrial emission reduction options.

Pollutant	Measure Name	Sector	Emission reduction	Investment	Yearly costs	Lifetime	Specific abatement costs		
			Mt CO <sub>2</sub> eq.	euro/tCO <sub>2</sub> eq.	euro/tCO <sub>2</sub> eq.	year	euro/tCO <sub>2</sub> eq.		
CO <sub>2</sub>	Application of continuous casting	Integrated iron and steel plant	1	557	-280	15	-230		
	Improved process control	Minimills	2	284	-274	15	-76		
	Miscellaneous	Petrochemicals	0.5	187	-92	15	-75		
	Debottlenecking	Petrochemicals	6	187	-92	15	-75		
	Miscellaneous I (Low cost tranche)	Pulp	2	200	-47	15	-67		
	Miscellaneous II (High cost tranche)	Pulp	2	1973	-271	15	-58		
	Process integration, e.g. by applying pinch technology	Petrochemicals	0.3	187	-54	15	-56		
	Ceramics - new capacity	Ceramics	3	0	-71	15	-54		
	Miscellaneous I (Low cost tranche)	Other industry	54	200	-47	15	-53		
	Electricity savings	Glass	0.2	1151	-271	15	-50		
	Fractionation - various options	Petrochemicals	0.3	469	-92	15	-50		
	Miscellaneous I (Low cost tranche)	Other Chemicals	38	200	-47	15	-49		
	Food, beverages and tobacco - miscellaneous I (Low cost tranche)	Other Food	20	216	-66	15	-49		
	Miscellaneous	Ceramics	11	187	-92	15	-47		
	Glass - new capacity	Glass	0.4	0	-51	15	-45		
	Miscellaneous - building materials	Other Building materials	6	188	-63	15	-44		
	Raising cullet percentage in raw material	Glass	1	0	-44	15	-44		
	Paper - New capacity	Paper	8	0	-45	15	-43		
	Electricity savings	Cement	1	1151	-271	15	-39		
	Cement - new capacity	Cement	5	0	-41	15	-38		
	Process integration, e.g. by applying pinch technology	Fertilisers	0.1	187	-54	15	-37		
	Food, beverages and tobacco - miscellaneous II (High cost tranche)	Other Food	28	532	-62	15	-35		
	Miscellaneous I (Low cost tranche)	Paper	14	200	-47	15	-35		
	Reduce dinker content of cement	Cement	1	0	-34	15	-34		
	Improving wet process kilns	Cement	2	0	-34	15	-34		
	Use of waste derived fuels	Cement	3	7	-34	15	-33		
	Optimisation of heat recovery of dinker cooler	Cement	1	29	-34	15	-31		
	Pulverised coal injection up to 30% in the blast furnace (primary steel)	Integrated iron and steel plant	1	200	-48	15	-30		
	Efficient CO <sub>2</sub> -separation (e.g. by using membranes)	Fertilisers	0.03	281	-54	15	-29		
	Improved drying, e.g. condensing belt drying	Paper	1	52	-30	15	-28		
	Miscellaneous II (High cost tranche)	Paper	11	667	0	15	-26		
	Cracking furnace - various options	Petrochemicals	0.2	750	-90	15	-23		
	Miscellaneous II (High cost tranche)	Other industry	54	667	0	15	-22		
	Miscellaneous	Sugar	4	187	-92	15	-12		
	Other non-ferro metals - miscellaneous	Other non-ferro	10	385	-46	15	-11		
	Batch and cullet preheating	Glass	1	269	-35	15	-11		
	Miscellaneous II (High cost tranche)	Other Chemicals	33	667	0	15	-11		
	Application of multi-stage preheaters and pre-calciners	Cement	0.2	673	-70	15	-10		
	Pressing to higher consistency, e.g. by extended nip press (paper making)	Paper	5	267	-20	15	-9		
	Application of efficient evaporation processes (dairy)	Dairy	1	567	-31	15	-8		
	Reduced air requirements, e.g. by humidity control in paper machine drying hoods	Paper	6	361	-21	15	-6		
	<b>Subtotal: Cost range &lt; 0 euro / t CO<sub>2</sub> eq.</b>			<b>334</b>					
	CO <sub>2</sub>	Integrated mills - new capacity	Integrated iron and steel plant	2	0	0	15	0	
		Scrap preheating in electric arc furnaces (secondary steel)	Minimills	0.3	0	0	15	0	
		Oxygen-enriched injection in electric arc furnaces (secondary steel)	Minimills	1	0	0	15	0	
		Minimills - new capacity	Minimills	15	0	0	15	0	
		Replacement of mercury and diaphragm processes by membrane electrolysis (chlorine)	Other chemicals	6	0	0	15	0	
		Miscellaneous I (Low cost tranche)	Iron and steel	12	200	-47	15	2	
		Refiner improvements	Pulp	1	752	-30	15	2	
		Improved melting technique and furnace design	Glass	1	366	-29	15	4	
		Low pressure ammonia synthesis	Fertilisers	0.01	469	-37	15	5	
		Fertilisers - new capacity	Fertilisers	0.2	469	-37	15	5	
		Gas turbine integration	Fertilisers	0.2	750	-56	15	11	
		<b>Subtotal: Cost range 0 &lt; 20 euro / t CO<sub>2</sub> eq.</b>			<b>38</b>				
		CO <sub>2</sub>	Heat recovery in TMP	Pulp	7	79	30	15	31
			Thin slab casting techniques	Iron and steel	1	802	-39	15	33
	Recovery of process gas from coke ovens, blast furnaces and basic oxygen furnaces (primary steel)		Integrated iron and steel plant	1	347	5	15	36	
Miscellaneous II (High cost tranche)	Iron and steel		11	667	0	15	47		
<b>Subtotal: Cost range 20 &lt; 50 euro / t CO<sub>2</sub> eq.</b>			<b>20</b>						
Advanced reforming	Fertilisers		0.1	1218	-45	15	65		
Retrofit existing Hall-Héroult process (e.g. alumina point-feeding, computer control)	Aluminium		0.5	6330	-274	15	72		
Efficient production of low-temperature heat (heat recovery from high-temperature processes)	Integrated iron and steel plant		2	1694	-18	15	135		
Wettable cathode	Aluminium		0.4	18086	-274	15	328		
<b>Subtotal: Cost range &gt; 50 euro / t CO<sub>2</sub> eq.</b>			<b>3</b>						

Pollutant	Measure Name	Sector	Emission reduction	Investment	Yearly costs	Lifetime	Specific abatement costs
			Mt CO2 eq.	euro/CO2 eq.	euro/CO2 eq.	year	euro/CO2 eq.
N2O	Industrial processes: Adipic acid	Chemical industry	66	232	24	15	0.1
	Industrial processes: Nitric acid	Chemical industry	22	238	106	15	0.4
<b>Subtotal: Cost range 0 &lt; 20 euro /t CO2 eq.</b>			<b>89</b>				
HFC	Industrial refrigeration: hydrocarbons and NH3	Food, Drink & Tobacco	1	36	-12	-9	-9
	Subtotal: Cost range < 0 euro /t CO2 eq.			1			
	Oxidation of HFC-23	Chemical industry	7	1	0.1	15	0.2
	Foam PU-one component: hydrocarbons	Other industry	3	4	0	15	0.4
	Foam PU-pipe in pipe: pentane	Other industry	0.1	27	0	15	2
	Industrial food refrig.: hydrocarbons and NH3	Food, Drink & Tobacco	2	164	-12	15	3
	Foams XPS : carbon dioxide	Other industry	6	11	5	15	6
	Aerosols : hydrocarbons	Other industry	2	85	3	15	10
	Foam PU-spray: water	Other industry	1	6	18	15	18
	Subtotal: Cost range 0 < 20 euro /t CO2 eq.			23			
	Foam PU-flexible faced laminate: pentane	Other industry	1	11	20	15	21
	Foam PU-discontinuous panels: pentane	Other industry	1	45	23	15	27
	Foam PU-blocks: pentane	Other industry	1	104	18	15	27
	Foam PU-continuous panels: pentane	Other industry	0.2	13	31	15	32
	<b>Subtotal: Cost range 20 &lt; 50 euro /t CO2 eq.</b>			<b>2.6</b>			
	Foam PU-appliances: pentane	Other industry	0.2	107	54	15	63
<b>Subtotal: Cost range &gt; 50 euro /t CO2 eq.</b>			<b>0.2</b>				
PFC	Aluminium: Side worked pre-baked anode cell (SWPB) conversion	Non-ferrous Metals	5	39	-6	15	-2
	Semiconductors: etch - alternative chemicals	Other industry	1	0	0	15	0.0
	Aluminium: Vertical stud oderberg anode (VS) retrofit	Non-ferrous Metals	0.3	39	-3	15	1
	Semiconductors: Chemical vapour deposition (CVD), NF3	Other industry	10	49	23	15	28
	Semiconductors: etch - oxidation	Other industry	3	79	71	15	79
<b>Subtotal: All cost ranges</b>			<b>20</b>				
SF6	Magnesium production: use of SO2 as protection gas	Non-ferrous Metals	3	4	0	15	0.3
	<b>Subtotal: Cost range 0 &lt; 20 euro /t CO2 eq.</b>			<b>3</b>			
Cost range < 0 euro /t CO2 eq.			340				
Cost range 0 < 20 euro /t CO2 eq.			153				
Cost range 20 < 50 euro /t CO2 eq.			33				
Cost range > 50 euro /t CO2 eq.			6				
<b>Total emission reduction potential</b>			<b>533</b>				

Figure 1. 1990 base year emissions (left, by gas) and 2010 frozen technology reference level (right, by cost bracket). The specific costs are calculated assuming a real interest rate of 4%. In all the cases the emissions are total emissions, i.e. direct emissions from the sector and indirect emissions (emissions from steam and electricity production allocated to the sector). The emission reduction potential includes the emission reduction attainable in the energy supply sector which can be allocated to the industry, based on its steam and electricity consumption.



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## 1. INTRODUCTION

Industrial activities have a substantial contribution to the total emissions of greenhouse gases in the European Union. The main part of the emissions is direct CO<sub>2</sub> emissions from combustion processes for direct heating and process emissions and indirect emissions related to steam and electricity consumption.<sup>2</sup> In this report, options are discussed to reduce direct emissions in the industry and to improve efficient use of steam and electricity.<sup>3</sup> Another substantial emission source of greenhouse gases is the emission of nitrous oxide from production of adipic acid and nitric acid production. The options to reduce these emissions are treated in chapter 3 of this report.

Emissions of industrial fluorinated gases are becoming increasingly important. The emission development and reduction options are discussed in another report<sup>4</sup>. Table 1.1 gives an overview of the greenhouse gas emissions in industry.

*Table 1.1. 1990 and 2010 frozen technology reference level direct and indirect emissions of greenhouse gases in the industrial sector, including process emissions [Primes, 1999; UNFCCC, 1999; sector report on fluorinated gases]. (Mt CO<sub>2</sub> equivalent).*

Industry sector		1990					2010				
		CO2	CH4	N2O	F-gases	Total	CO2	CH4	N2O	F-gases	Total
Austria	AUT	33	0	1	1	34	45	0	1	2	47
Belgium	BEL	52	0	5	1	58	71	0	4	2	76
Germany	DEU	402	0	34	16	451	510	0	33	23	566
Denmark	DNK	20	0	1	0	21	24	0	1	1	26
Spain	ESP	96	0	8	9	113	146	0	6	10	162
Finland	FIN	22	0	2	0	24	42	0	1	1	44
France	FRA	125	0	29	9	163	196	0	29	12	237
United Kingdom	GBR	219	0	33	10	262	326	0	34	12	372
Greece	GRC	37	0	2	1	40	49	0	1	1	52
Ireland	IRL	12	0	2	0	14	21	0	1	0	23
Italy	ITA	174	0	16	7	198	214	0	14	8	236
Netherlands	NLD	57	0	10	8	75	81	0	9	5	95
Portugal	PRT	20	0	1	0	21	33	0	1	1	35
Sweden	SWE	19	0	2	1	21	31	0	1	3	35
European Union	EU	1287	3	143	63	1495	1789	3	135	81	2007

Numbers may not add up to EU total due to rounding

Source: Primes (1999); UNFCCC (1999); sector study on fluorinated gases; this study.

The description of the frozen technology reference level for 2010 will be given in the following two chapters.

<sup>2</sup> Emissions due to mining activities, and emission due to transport and distribution of base material and products are not allocated to industrial activities.

<sup>3</sup> Options to improve efficiency of steam and electricity generation are treated in the report on energy supply. "Economic Evaluation of Emission Reduction of Greenhouse Gases in the Energy Supply Sector in the EU - Bottom-up Analysis", C. Hendriks et al. Ecofys, January 2001.

<sup>4</sup> The options to reduce emission of fluorinated gases are not described in this report but in the report "Economic Evaluation of Emission Reductions of HFCs, PFCs and SF<sub>6</sub> in Europe", J. Harnisch and C. Hendriks, Ecofys, March 2000.

## 2. OPTIONS TO REDUCE CO<sub>2</sub> EMISSIONS BY INDUSTRIAL ENERGY-EFFICIENCY IMPROVEMENT

### 2.1 INTRODUCTION

In this section the potential for reducing the emissions of the greenhouse gas CO<sub>2</sub> by improving the end-use energy efficiency of industrial activities in the EU Member States is assessed. Energy-efficiency improvement is defined here as a decreased consumption of non-renewable final energy carriers without affecting the level or nature of the activity for which the energy is used. It should be noted that many industrial energy efficiency improvement measures also affect product quality. In fact, energy efficiency improvement measures that simultaneously achieve non-energy benefits are much more likely to be adopted. As long as the level or nature of the activity is not affected, such measures are taken into account (for instance a new pressing technique in the paper industry that results in energy savings and improved product quality). On the other hand, dissemination of information through the internet instead of on paper, which might result in a reduction of the use of paper<sup>5</sup>, is not taken into account. The reason is that the level of the activity, namely paper making, might be affected. Improvement of the efficiency of the conversion of fossil fuels to final energy carriers in boilers, CHP-plants and power plants are covered the report on energy supply.

In 1990 the direct fossil fuel-related CO<sub>2</sub> emissions from industry in the EU member countries equalled 424 Mt, or 14% of the total EU CO<sub>2</sub> emissions. Table 2.1 gives a subdivision of the industrial CO<sub>2</sub> emission into sectors per Member State. The data are taken from PRIMES [1999].

Table 2.1. 1990 direct CO<sub>2</sub> emissions from fossil fuel consumption by industrial sectors in EU-Member States [PRIMES, 1999].

Mtonne CO <sub>2</sub>	EU	AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	NLD	PRT	SVE
Iron and Steel	174.7	5.9	16.7	57.5	0.3	11.4	3.1	24.0	23.0	0.4	0.1	20.0	7.3	0.8	4.0
Non-ferrous metals	16.2	0.1	0.5	5.2	0.0	0.9	0.1	4.6	1.6	1.2	0.8	0.8	0.2	0.1	0.3
Chemicals	26.2	0.3	1.9	7.6	0.0	2.7	0.3	1.6	1.3	0.3	0.3	5.7	4.1	0.1	0.1
Building materials	98.1	1.8	3.1	25.9	1.8	11.1	2.9	13.2	8.8	4.2	0.3	18.4	2.2	3.0	1.6
Paper and Pulp	10.6	0.3	0.1	1.1	0.3	2.2	0.2	2.2	0.7	0.2	0.0	1.9	0.2	0.0	1.2
Food, drink, tobacco	10.7	0.1	0.5	4.1	0.2	0.6	0.2	1.4	1.4	0.2	0.2	0.6	0.9	0.2	0.2
Engineering	39.3	0.2	0.7	17.3	0.4	1.5	0.4	4.9	7.0	0.0	0.3	4.5	1.1	0.1	0.8
Textiles	2.1	0.0	0.1	1.0	0.0	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.1	0.3	0.1
Others	46.3	0.9	1.9	6.0	0.6	2.1	2.1	6.1	13.4	1.2	2.1	7.1	1.0	1.0	0.9
<b>Industry total</b>	<b>424.1</b>	<b>9.7</b>	<b>25.3</b>	<b>125.8</b>	<b>3.6</b>	<b>32.5</b>	<b>9.2</b>	<b>58.0</b>	<b>57.5</b>	<b>7.8</b>	<b>4.0</b>	<b>58.9</b>	<b>17.1</b>	<b>5.5</b>	<b>9.1</b>

Notes: Data for Luxembourg are included in the data for Belgium; CO<sub>2</sub> emissions that stem from the production of steam and electricity are not included in these data.

<sup>5</sup> The effect of the internet on the amount of paper consumed still cannot be predicted. The paper consumption might also increase.

The CO<sub>2</sub> emissions from steam and electricity generation are not included in the emission data presented in Table 2.1. The emission data for the iron and steel industry include the emissions that stem from the use of carbon as reducing agent of iron ore, since most of this carbon is emitted as carbon dioxide to the atmosphere at the steel plants. Also included is the CO<sub>2</sub> emitted during the clinker making for cement production. On the other hand, the carbon that is embodied in chemical products is not released at the production site and is therefore not included in the emission data from the chemical industry.

## **2.2 METHOD**

### **2.2.1 Description of the method**

A bottom-up method is used to determine the potential for energy-efficiency improvement. This means that starting at a detailed level, e.g. the level of industrial operations or subsectors, a picture is obtained of the energy-efficiency improvement potential at an aggregated level, e.g. an industrial sector in the EU as a whole. The more detailed the bottom level the better the potential can be founded. The best indication of the potential would probably be obtained if energy-efficiency improvement measures were identified at plant level. However, data availability and time constraints impede working at this level. In this study the level of industrial subsectors is used and the most important unit operations are treated separately.

The base year for the assessment of the potential for energy-efficiency improvement is 1990. Thus, data for the year 1990 are used as reference, even when more recent data are available. The future reference year is 2010. Only measures that have a high probability of being commercially available before 2010 are included.

Between 1990 and 2010 the industrial production is expected to grow. The net growth is the result of both an increase in capacity by new plants or expansion of the capacity of existing plants and - by decrease in capacity - by plants that are taken out of operation. New plants can be built with an energy efficiency that is better than that of the old capacity. We assume that this efficiency will equal the best practice value<sup>6</sup> of 1995. We also assume that the net growth will be totally met by new capacity. This is illustrated in figure 2.1. On the one hand, this is an overestimate of the contribution of new capacity because part of the growth will be met by expanding existing capacity. On the other hand, this is an underestimate because part of the existing capacity, generally less efficient than the average, will be taken out of operation in the period 1990-2010.

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<sup>6</sup> Best practice means the best that has been realised in an existing plant. Note the difference with best available technologies, which have not been always realised.

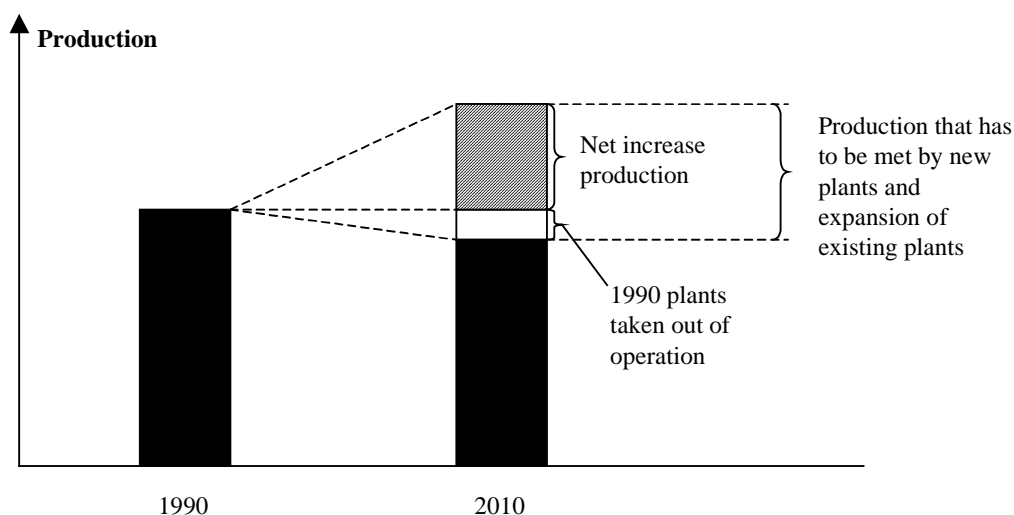


Figure 2.1. Illustration to show how is dealt with new capacity.

The additional investment cost and operation and maintenance costs for new capacity with a best practice energy consumption are assumed to be zero.

The following procedure is followed to determine the *potential for reduction of GHG emissions* per sector and per EU Member State. An example is worked out in Annex 1.

1. Per sector options are identified for the reduction of the fuel or electricity demand.
2. Per sector and per country the 1990 specific energy consumption (SEC), distinguishing fuel and electricity consumption, is determined, expressed in GJ fuel or electricity per unit of activity.
3. Per option the technical potential for savings on fuel and electricity demand is determined, expressed in GJ fuel or electricity saved per unit of activity.
4. Per option and per country a maximum technical saving potential on fuel or electricity demand is determined as if the option had not been implemented at all, expressed in terms of percentage of the SEC. This is done by dividing the technical saving potential (3) by the SEC (2).
5. Per country the 1990 degree of implementation of each option is determined, expressed in % of the fuel or electricity demand of the sector. If data on penetration are available, these data are used. Otherwise, an estimate is made on the basis of the SEC of related technologies.
6. Per country the maximum degree of technical implementation in 2010 for each option is determined, expressed as percentage of the fuel or electricity demand of the sector. This is estimated on the basis of the expected development of the technology and technical constraints to the implementation of the technology.
7. Per country the share of the fuel or electricity consumption of the sector to which each option is applicable is determined.

8. The potential saving on fuel or electricity demand can now be determined as follows:

$$\text{annual potential saving} = (\text{implementation in 2010 (6)} - \text{implementation in 1990 (5)}) \\ \times \text{maximum technical saving (4)} \times \text{share (7)}$$

The potential savings are expressed as a percentage of the fuel or electricity demand of the sector.

9. The potential savings on GHG emission by sector and by country can be determined by multiplying the potential savings of fuel and electricity (8) by the CO<sub>2</sub> emission factors of fuel use and electricity use by sector and by country.

The following procedure is followed to determine the *cost parameters* per option.

1. Per option the specific investment costs and specific annual operation and maintenance (O&M) costs are determined, expressed in €/GJ of final energy saved per year. No distinction is made between countries. The figures are obtained from literature and expert consultation.
2. Per option the benefits from saved energy purchase costs are determined based on country specific energy prices, detailed by sector for fuel and electricity, expressed in €/GJ saved annually.
3. Using a pre-set discount rate and the technical lifetime for each option the annualised specific investment costs are calculated.
4. The total annual specific costs for efficiency improvement are obtained by adding the specific annualised investment costs and the specific O&M costs and subtracting the saved energy purchase costs. These costs are expressed in €/GJ saved annually.
5. The annual specific costs for GHG emission abatement are obtained by dividing the specific costs from (4) by the sector-specific and country-specific CO<sub>2</sub> emission factor.

Example: A measure has investment costs of € 50/GJ of electricity saved and additional O&M-costs of € 0.5/GJ of electricity each year. With a lifetime of 15 years and a discount rate of 4% the annuity factor is 0.09. Annual costs are € 50\*0.09 = 4.50 + € 0.5 = € 5 /GJ of electricity saved annually. Knowing that 1 GJ of electricity equals 278 kWh and the industrial price of electricity is in the ballpark of 4 eurocents per kWh, saving 1 GJ of electricity saves about € 11.1. The total specific annual specific costs of this measure are € 5 – € 11 = € -6/GJ saved (with a discount rate of 4%).

### 2.2.2 Restrictions and uncertainties

The method used in this report is designed to obtain an estimate of the potential for energy-efficiency improvement per industrial sector and for the industry as

a whole per EU Member State. The results cannot be used to carry out evaluations at plant level nor should potentials for subsectors per Member State be compared.

The estimate of the potential for energy-efficiency improvement requires the collection of many data, many of which are not exactly known. Therefore, some remarks should be made on the uncertainties in the data:

- Uncertainties in degrees of implementation in 1990: While for some technologies data are available on current market shares, there is still a lack of statistical basis for many technologies. In these cases estimates were based on a comparison of the SEC with that of a country for which degree of implementation are known. In some cases, penetration rates have also been estimated on the basis of the state of technology (e.g. only recently commercialised).
- The maximum degree of implementation in 2010 is based on a perception of technical constraints, e.g. space available and adaptability of existing operations. An accurate estimate does not only require insight in the situation per industrial site (e.g. interaction of steam flows) at the moment but also the development of this situation up to 2010. Such information is not available and it can be doubted if it ever will be. Our estimate is therefore based on general statistics and information, complemented with expert judgement in some cases.
- Data on the costs of energy-efficiency improvement are not available for all options and all countries. Cost estimates are generally based on information obtained from one or more plants. Local conditions that might effect energy-efficiency improvement potentials or associated costs have not been taken into account.
- Uncertainty in reference technologies. To account only for the costs for energy-efficiency improvement, cost data are reported as additional to a reference technology. The reference technology should be a technology that can perform the same function as the efficient technology and represents the average choice of the investors. The reference technology does not have to be the same for all EU Member States and even in one Member State there may be a discussion about which reference technology should be used.
- Cost data only include direct investments and operation and maintenance costs. Costs for acquiring information and decision making, the so-called transaction costs<sup>7</sup>, are not accounted for.

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<sup>7</sup> Transaction costs are resources that have to be used to carry out a market transaction, i.e. to identify a market, to formulate one's own demand, to negotiate and conclude the contract and to monitor and control its execution (definition by Coase cited in Ostertag [1999]). Frequently, transaction costs are used in a much wider sense, comprising all cost impacts resulting from energy efficiency measures which have not been fully accounted for in cost analysis [Ostertag, 1999].

## 2.3 IRON AND STEEL INDUSTRIES <sup>8,9</sup>

### 2.3.1 Key parameters

In 1990 all EU countries had steel production facilities, see Table 2.2. Four countries, Germany, Italy, France and the United Kingdom, account for nearly three-quarters of the total EU production. Integrated steel plants, based on blast furnaces and basic oxygen furnaces (BOF), accounted for 70% of the crude steel production, the balance being produced in electric arc furnaces (EAF). Only in the former GDR some steel was made in the obsolete Open Hearth Furnace. This is not included in the table. Whereas in 1990 steel making in Luxembourg was completely based on the BOF-route, since August 1997 it is 100% EAF-based. Between 1994 and 1997 three EAF plants were built and the sinter plants, blast furnaces and BOFs were decommissioned.

Table 2.2. Production figures for crude steel (1990), divided into steel made in Basic Oxygen Furnaces (BOF) and Electric Arc Furnaces (EAF) [IISI, 1996, 1995].

Process	production of crude steel (million tonnes)															
	AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SW E	EU
BOF	3.9	10.4	31.3		5.6	2.4	13.6	13.2			11.2	3.6	5.3	0.3	2.7	103.5
EAF	0.0	1.0	7.1		7.2	0.5	5.1	4.7			14.3	-	0.2 <sup>3</sup>	0.4	1.7	42.2
Total	3.9	11.4	38.4	0.6 <sup>2</sup>	12.8	2.9	18.7	17.8	1.0	0.3 <sup>3</sup>	25.5	3.6	5.5	0.7	4.5	147.7

<sup>1</sup> FRG only; <sup>2</sup> EC, 1993. Data for 1991; <sup>3</sup> De Beer *et al.*, 1994.

In statistics, specific energy consumption is not reported by steel making process. However, figures can be derived from the IISI publication “Statistics on Energy in the Steel Industry –1996 Update” [IISI, 1996] figures can be derived. To do so, it was necessary to divide the energy consumption for rolling and finishing over BOF and EAF steel. This was done on the basis of their production ratio<sup>10</sup>. Furthermore, data on energy consumption were rarely divided into BOF and EAF. In these cases, it was assumed that the energy consumption for making BOF-steel was 0.8 GJ/tcs. The energy consumption for making EAF-

<sup>8</sup> The European Independent Steel Works Association (EISA) commented on a draft version of this section. Their main comment was that it is difficult to verify the validity of the data. Due to lack of time it was not possible to discuss the data with EISA. Specific comments have been added in footnotes to the text.

<sup>9</sup> Eurofer co-operated with Ecofys in the production of the report (written comments and a meeting with them). Eurofer commented that although the report provides a useful summary of theoretical possibilities Eurofer cannot subscribe to figures on potential savings based on a methodology that is not appropriate for the purpose of identifying the energy savings or energy efficiency improvements from this sector.

<sup>10</sup> Products from EAFs are generally less processed than products from BOFs. The energy consumption for rolling and finishing from EAFs should therefore also be less. However, due to lack of data this effect is taken into account in this study.

steel was then calculated<sup>11</sup>. For Austria, Germany, Spain, Finland, France, United Kingdom and Luxembourg no SEC for coke production was reported. For these countries a figure of 4.0 GJ/tonne crude steel is assumed [IISI, 1998]. To be able to do the calculations it was assumed that all electricity consumed in integrated steel plants is produced in-house, i.e. only fuel is bought. It is also assumed that in EAF-plants all electricity is bought. In practice, the division between in-house generated and purchased electricity varies considerably from plant to plant. It should be noted that on average the injection of pulverised coal into EAFs can make up 10-15% of the SEC of EAFs. For Denmark, Greece, Ireland, Italy and Portugal no data on SEC were reported in the IISI-publication. For Denmark, with only EAF, we assume the same value as for Sweden. For Greece, Portugal and Italy we assume the same values as for Spain. For Ireland we assume the same values as for United Kingdom. IISI does not report a value for EAF in the Netherlands. We assume here the same value as in Germany.

The data are based on many assumptions that make them uncertain. In general it appears that the SEC for integrated steel plants is a little too high and for mini mills is a little too low in this report. It should also be noted that the SEC depends on the product mix. An update of these data is recommended. See Table 2.3. Readers are referred to the section on methodology, which discusses the limitations that apply to the estimates and the purposes for which they should be used.

*Table 2.3. Specific fuel consumption for the production of crude steel in Basic Oxygen Furnaces and specific electricity consumption for steel made in Electric Arc Furnaces (EAF). Derived from [IISI, 1996]. Values in italics are assumptions based on comparative countries. Data are valid for 1990.*

Process	AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
specific fuel consumption (GJ/tonne crude steel)															
BOF	23.9	32.1	30.6	-	30.8	25.7	29.4	27.9	30.8	27.9	30.8	23.6	20.9	30.8	29.2
specific electricity consumption (GJ/tonne crude steel)															
EAF	5.5	4.6	6.3	5.6	3.7	4.7	4.0	4.7	3.7	4.7	3.7	<i>.<sup>2</sup></i>	6.3	3.7	5.6

<sup>1</sup> FRG only. <sup>2</sup> In 1990 Luxembourg had no EAF capacity.

### 2.3.2 Options to improve the energy efficiency

The following options to improve the efficiency in the iron and steel industry have been identified:<sup>12</sup>

- Injection of pulverised coal and plastics waste in blast furnaces;
- Heat recovery from sinter cooler air;

<sup>11</sup> This assumption had to be made for the following countries: Germany, France, Finland, Spain and United Kingdom.

<sup>12</sup> A way to reduce emissions is to change from blast furnaces to electric arc furnaces. This option is not taken into account in this study.

- Recovery from energy in process gases from the blast furnace and the basic oxygen furnace;
- Application of continuous casting;
- Efficient recovery of low-temperature heat;
- Scrap preheating in electric arc furnaces;
- Oxygen and fuel injection in the electric arc furnace;
- Improved process control in mini mills;
- Thin slab casting;
- Miscellaneous measures.

*Injection of pulverised coal and plastics waste in blast furnaces* - Injection of fuel, particularly pulverised coal, into the blast furnace to replace part of the coke is already a common measure in many countries. The maximum injection rate has still to be determined but is estimated at 280-300 kg of pulverised coal per tonne of pig iron. Experiments with such a high injection rate at the Dutch iron and steel plant (Hoogovens) turned out to be a failure [De Jong, 1999]. The highest injection rate achieved so far is 225 kg/tonne pig iron, amongst others at Hoogovens. This means that about 40-45% of the energy and feedstock required by the blast furnace is injected in the form of pulverised coal, the remainder being mainly coke.

The maximum injection rate depends amongst others on the shape and size of the blast furnace. The 1990-injection rate of coal and oil is known for countries that are included in the IISI-report [IISI, 1996]. For other countries we assumed an injection rate of 5%. Notably Germany, Finland, Luxembourg and the United Kingdom use oil injection instead of coal injection. See Table 2.2.

Table 2.4. *Injected energy as a percentage of the total energy input in blast furnaces in 1990 [IISI, 1996].*

1990 injection rate of energy in the blast furnace (% of total energy input)														
AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
9%	10%	15%	-	7%	15%	15%	15%	5%	0%	5%	17%	30%	5%	9%

<sup>1</sup>FRG only

Coal injection results in energy savings at coke making. Per tonne of coke that is replaced about 1.08 tonne of coal is required [Worrell *et al.*, 1999]. The energy saved is on average 3.5 GJ/tonne coke replaced (the energy requirement for coke making [IISI, 1998] minus the energy content of the extra coal required). When the coal injection rate is increased from 0 to 30% of the energy input into the blast furnace, the energy savings are about 0.5 GJ per tonne crude steel.

The maximum technical penetration of coal injection depends on size of blast furnace and ore characteristics. In some cases coal injection is too expensive or injection of other fuels is more favourable. Therefore, the maximum penetration is set at 75%.

Capital costs are related to the need for coal grinding equipment and amount to 50-55 €/tonne of coal injected (or 10-11 €/GJ saved annually) [Worrell *et al.*, 1999]. Additional operation costs are related to extra oxygen injection and operation of the grinding line. This is offset by the reduced costs for operation of the coke ovens. A saving on fuel costs is achieved as injectant coal is about 10% cheaper than coking coal, equalling 1 €/GJ saved annually.

Another option is the use of plastic waste as a reducing agent instead of coal (or fuel oil). In Germany, a part of the plastic packaging waste collected by DSD (Duales System Deutschland) is processed using this technology (e.g. in the blast furnace of the steelworks in Bremen).

*Heat recovery from sinter cooler air* - The recovered heat can be used to pre-heat raw material or combustion air or to produce steam. Sinter plant heat recovery has been applied in several integrated mills world wide [AISI, 1998; Worrell *et al.*, 1999]. Energy savings are estimated at 0.55 GJ/tonne sinter; the electricity demand increases by 1.5 kWh/tonne sinter. These data are based on a retrofitted system at Hoogovens, the Netherlands [Worrell *et al.*, 1999]. Capital costs are estimated at 3 US\$/tonne sinter. However, the sinter plant of Hoogovens is relatively small and not typical for European sinter plants.

The amount of sinter used per tonne of crude steel varies strongly from country to country (see Table 2.5). This depends on the amount of other iron sources that can be used, e.g. scrap, pellets and iron ore fines. The amount of sinter used determines the saving potential from heat recovery from sinter cooler air. We assume this amount remains constant for the whole period up to 2010.

In the database the highest sinter input (France) is indexed at 100%. In France, with a sinter input of 1.51 tonne/tonne crude BOF-steel, 0.83 GJ of fuel can be saved per tonne crude steel; the increase in electricity demand is neglected. The savings in all other countries are related to the saving in France. For example, the saving in Belgium is  $1.13/1.51=75\%$  of 0.83 GJ/tcs is 0.62 GJ/tcs.

*Table 2.5. Country average sinter input per tonne of crude steel produced in BOFs in 1990(tonne sinter/tonne crude steel) [IISI, 1996]. Values in italics are estimates on the basis of comparative countries.*

tonne sinter/ tonne of BOF crude steel															
AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	
1.06	1.13	0.88	0.00	1.10	1.26	1.51	1.04	1.10	1.04	1.10	1.30	0.75	1.10	0.41	

<sup>1</sup> FRG only

Sinter plant heat recovery is installed at numerous mills in Europe [Worrell *et al.*, 1999]. However, data on the penetration of the technology are not available. Penetration is restricted by space availability (at some sites there is simply no space to install a heat recovery system) and applicability of recovered steam. It is assumed that the additional potential saving compared to 1990 is negligible.

*Recovery of energy in process gas from blast furnace and basic oxygen furnace*  
- Process gases contain energy in the form of heat, chemicals and pressure. Various options are available to recover these forms of energy.

- A recovery system developed and installed at Hoogovens recovers 1.55% of the gas that is lost during charging of the blast furnace. Savings are estimated to be 66 MJ/tonne hot metal at a cost of €0.3/tonne hot metal [Farla *et al.*, 1998].
- Blast furnaces that are operated at a pressure of 4-5 bar can be equipped with turbines that recover part of the energy of the top gas in the form of electricity. The gas has to be cleaned before entering the turbine. In the common wet cleaning system the temperature of the gas decreases from 150° to 40°C [IISI, 1998a]. Using a dry cleaning system up to 30% more energy can be recovered. However, such a system has not been implemented and it is far more expensive than the wet cleaning system. Wet top gas recovery turbines can only be operated at furnaces with a high pressure and the economics are more favourable at larger furnaces. The electricity production is in the range of 20-40 kWh/tonne pig iron [IISI, 1998a; Worrell *et al.*, 1999]. Capital costs are US\$20/tonne pig iron [Worrell *et al.*, 1999]. Operation and maintenance costs are estimated at € 0.2/tonne pig iron. This technology is already very common in Europe. The maximum penetration is limited to about 80%. The remainder of the furnaces has a pressure that is too low for economic exploitation of this technology.
- By avoiding combustion of BOF-gas each time the converter is opened for charging or discharging, BOF-gas can be recovered and used as fuel. This system is known as suppressed combustion. The sensible heat can be recovered in a waste heat boiler. An additional environmental benefit is the reduced dust emission. The dust, with a high metal content, can be recycled in the sinter plant. BOF gas recovery can be optimised by using an expert system and pressure control [IISI, 1998a]. Total energy savings are 0.6-1.0 GJ/tonne of liquid steel [Worrell *et al.*, 1999; IISI, 1998a]. Suppressed combustion can make a basic oxygen furnace a net energy producer. Capital costs are € 22 /tonne of liquid steel [Worrell *et al.*, 1999].

The total amount of energy that can be recovered from BF and BOF is 0.9-1.4 GJ/tonne of liquid steel. The recovered electricity is expressed as saved fuel (efficiency 40%) assuming that most electricity is generated on site. The potential savings for each country are assumed to be dependent on the 1990 efficiency. If the SEC is higher than 25 GJ/tonne it is assumed that the 1990 penetration of the technologies is 0%, if the SEC is lower than 25 GJ/tonne the 1990 penetration is assumed to be 10%. The maximum penetration is limited by the size and age of the furnaces. Older furnaces work under a pressure that is too low for pressure recovery. Since most furnaces in Europe are older than 25 years it is assumed that the maximum penetration is 20%.

The investment costs of the measure with the largest saving – suppressed combustion - are used: €22/tonne of steel (€ 9/GJ saved annually). Operation and maintenance costs are estimated at 10% of the investment costs.

*Application of continuous casting* - In 1998 the penetration of continuous casting was 83.3% world wide. Penetration in European countries is even higher. Table 2.6 shows the penetration in 1990 and 1998 [IISI, 1996, 1999]. Continuous casting is now a mature technology and is in general exploited to its maximum. Therefore, it is assumed that the 1998 penetration is the maximum penetration.

Table 2.6. *Continuous casting as share of crude steel output for 1990 and 1998 (both BOF and EAF steel) [IISI, 1996, 1999]. Data in italics are assumptions.*

continuous casting (share of crude steel output)														
AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
1990 [IISI, 1996]														
99%	98%	91%	99%	97%	98%	95%	80%	99%	99%	99%	35%	97%	99%	88%
1998 [IISI, 1999]														
97%	99%	96%	99%	96%	99%	95%	94%	99%	99%	99%	96%	98%	99%	88%

<sup>1</sup>FRG only

The remainder of the crude steel was cast as ingots. Ingot casting requires about 1.5-3.0 GJ/tonne steel additional to continuous casting. Investment costs are 69 €/tonne cast steel (€ 31/GJ saved annually) [Worrell *et al.*, 1999]. Operation cost can be reduced significantly compared to ingot casting: -31 €/tonne cast steel (€ -14/GJ saved annually) [Worrell *et al.*, 1999].

*Other options for efficient recovery of low-temperature heat* – An integrated steel plant has a number of high-temperature processes. Several techniques are available to recover the heat that would otherwise be lost:

- Coke dry quenching. The sensible heat of the hot cokes contain half of the energy input to the process [IISI, 1998a]. In conventional wet quenching this energy is lost to the atmosphere. Coke dry quenching cannot only recover part of this energy, but also reduce dust emissions from coke plants. Dry coke quenching is typically installed as an environmental control technique [Worrell *et al.*, 1999]. The coke is quenched by an inert gas and the heat is used to produce steam. This steam can, for instance, be used to generate electricity. Coke dry quenching has been implemented at several plants in Japan, Germany, Brazil, Finland and Taiwan [Worrell *et al.*, 1999]. The steam production equals 0.8-1.4 GJ/tonne of coke [Worrell *et al.*, 1999; IISI, 1998a]. Since it is not expected that many new coke plants will be built in Europe, retrofit capital costs should be used: 70 €/tonne coke. Operation and maintenance costs are estimated to increase by 0.5 €/tonne coke compared to wet coke quenching.
- Heat recovery from hot stove waste gas.
- Heat recovery from blast furnace slag.

- Recuperative burners at the reheating furnace. Separate heat recovery from combustion air is already common in modern steel plants. Additional savings that can be attained by using recuperative burners are small. Therefore, this measure can only be applied economically to furnaces that have no heat recovery at all (20% in the western world [Worrell et al., 1999]). The fuel savings is 0.7 GJ/tonne product on average and investment costs are estimated at € 2.5/tonne [Worrell et al., 1999].
- Heat recovery from sinter cooler air (see above)
- Blast furnace dry cleaning top gas recovery. This technique is already dealt with under ‘recovery of energy from process gases’.
- Suppressed combustion of basic oxygen furnace gas. This technique is already dealt with under ‘recovery of energy from process gases’.

We estimate the total saving of low-temperature heat recovery at 0.5-1.0 GJ/tonne crude steel, excluding the potential of techniques that were dealt with separately. Investment costs are set at 70 €/tonne steel (€ 93/GJ saved annually). Implementation is very site specific and is estimated at 50% at maximum.

*Scrap preheating in electric arc furnaces* - Preheating of the scrap before being charged into the furnace by use of the hot off-gases of the furnace is a way to save on the power demand for melting. However, extra energy is required to treat the off-gases and the balance is not always positive. Two technologies are in use: the Finger Shaft Furnace and Conroll. Scrap preheating in the Finger Shaft Furnace is achieved by holding the scrap in a bucket above the furnace. Cooled fingers in the form of a grab at the bottom of the bucket hold the scrap in place. When the preheating stage is finished the grab is released and the scrap is loaded into the melt. In the Conroll process scrap is preheated in a long tunnel with counter current off-gases and auxiliary burners. The scrap is fed continuously into the furnace.

With both systems a saving of about 80 kWh/tonne liquid steel can be achieved [IISI, 1998a]. Both systems have already been applied to numerous furnaces in USA, Europe and Japan. An additional fuel consumption of 0.2 GJ/tls is required [De Beer *et al.*, 1998]. Applying scrap preheating to existing furnaces is often technically unfeasible due to space limitation. It is assumed that this technique will only be applied to 10% of the capacity. Extra investment costs are estimated at € 4.5-5.5/tonne liquid steel (€ 50/GJ saved annually) [Worrell *et al.*, 1999]. The annual costs savings due to increased productivity, reduced electrode costs and increased yield are estimated to be € 1.9/tonne liquid steel (€ -19/GJ saved annually).<sup>13</sup>

*Oxygen and fuel injection in the electric arc furnace* – Injection of oxygen and fuel can improve the energy efficiency of an electric arc furnace in the following ways:

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<sup>13</sup> EISA commented that the data given with this measure do not correspond to any figures available at industry site.

- Post-combustion. During the melting and refining of steel carbon monoxide is released. By injecting oxygen this carbon monoxide can be post-combusted and the heat released can be returned to the molten steel bath. Post-combustion is also used in oxy-steel making and is studied closely in relation to smelt-reduction. The technique can result in an increased productivity of the electric arc furnace.  
The savings on electricity demand are in the range of 20-40 kWh/tls [IISI, 1998a]. However, an oxygen consumption of about 9 Nm<sup>3</sup>/tls is required [IISI, 1998a]. To make this oxygen 5 kWh/tls is needed. We assume net savings of 25 kWh/tls. Investment costs are estimated at € 1/tls.
- Foamy slag practice. A foamy slag, obtained by carbon or oxygen injection, reduces the heat losses from the melt. Savings are estimated at 5-7 kWh/tls [Worrell et al., 1999]<sup>14</sup>. Capital costs for installing oxygen lances are estimated at € 10/tonne capacity. On the one hand, there are additional costs for operation of the lances and for oxygen. On the other hand, increased productivity results in annual costs savings, which are estimated to be € 1.8/tls [Worrell et al., 1999]. We assume overall annual costs savings of € 1/tls. Applying foamy slag practice is a quite common technology [Worrell et al., 1999].
- Oxy-fuel burners. Burning oil or natural gas can replace part of the electricity demand of an electric arc furnace. Oxy-fuel burners can be positioned at the side wall to impinge on cold spots. Another arrangement is a single burner through the work door. The savings depend on burner power and burner operation. Burner power is determined by the size of the furnace and burner operation depends on melting practice and configuration of the furnace.  
Per Nm<sup>3</sup> of natural gas about 6.8 kWh/tls can be replaced [IISI, 1998a]. Typical savings are on the order of 30-70 kWh/tls [IISI, 1998a]. In this study we assume an average of 50 kWh/tls. To replace this electricity demand about 6 Nm<sup>3</sup> of gas is required, equalling 0.24 GJ<sup>15</sup>.  
Capital costs are estimated at € 4.80/tls [Worrell et al., 1999]. Application of oxy-fuel burners can lead to reduced tap-to-tap times [IISI, 1998a] and reduce the nitrogen content in steel [Worrell *et al.*, 1999]. These advantages lead to an improvement of the operation costs of € 0.4/tls. Oxy-fuel burners are a quite common technology in developed countries.

Overall a saving of 80 kWh/tls on electricity demand is assumed. The fuel demand will increase by 0.24 GJ/tls. Average investment costs are € 3.5/tls (€ 70/GJ saved annually) and operation and maintenance costs are € -0.25/tls (€ -5/GJ saved annually). Penetration in 1990 is assumed to be 60% in all EU member countries. Maximum penetration is limited to 80% due to technical constraints.

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<sup>14</sup> EISA states that the savings with foamy slag practice are much more significant and range from 15-30 kW/ton but depend on the type of EAF taken into consideration. According to EISA the information on foamy slag practice can certainly be deepened.

<sup>15</sup> Assuming a lower heating value of 31.65 MJ/Nm<sup>3</sup> natural gas (Dutch Standard).

*Improved process control in mini mills* - Artificial intelligence techniques, e.g. fuzzy logics or neural networks, can be applied to optimise the energy input. Especially with the complex heating schemes that are used in modern ultra high power (UHP) furnaces this type of control systems is necessary [AISI, 1998]. The savings depend on the raw material input, the type of furnace and the furnace operation. In line with [Worrell et al., 1999] we assume that savings of 30 kWh/tcs are possible on average. Other advantages of automated controls are an increased productivity and a lower electrode consumption. Worrell et al. [1999] estimate the capital costs at € 0.95/tonne steel (€ 9/GJ saved annually). We assume that the savings that could be achieved by systems available in 1990 were small compared to the currently available systems. On top of this, the 1990-penetration was low. Therefore, we assume a zero penetration in 1990.

*Thin slab casting* – Thin slab casting allows casting of thinner slabs (40-125 mm) than with continuous casting (150-300 mm). Less energy is required to reheat the slabs before rolling. Thin slab casters were originally designed for minimills, but are now being constructed or planned by some integrated steel manufacturers. IISI [1998a] reports the following data for the energy consumption of an actual thin slab caster (CSP-technology): 250 MJ of electricity/tonne and 350 MJ fuel/tonne. Continuous casting, reheating and hot rolling use about 4 GJ of fuel and 0.6 GJ of electricity per tonne of slabs. Thus, assuming that 40% of the steel production is on average in the form of slabs, the savings amount to 1.5 GJ of fuel and 0.15 GJ of electricity per tonne steel.

Investment costs for constructing new thin slab casters at Hoogovens and Thyssen are € 200/tonne rolled steel and € 300/tonne rolled steel, respectively [De Beer *et al.*, 1998]. We assume that the lower costs can also be realised at future projects (€ 48/GJ saved annually). Operation and maintenance costs are 80% to 110% of that for continuous casting. We estimate the average reduction in O&M-costs at € 0.5 /tonne rolled steel compared to continuous casting (€ - 0.1/GJ saved annually).

Thin slab casters can only be applied to the production of slabs. Furthermore, it competes with continuous casting, which is a mature technology. Since thin slab casting is not yet a proven technology for integrated steel mills, we assume a maximum penetration of 7% of the crude steel production in 2010. Thin slab casting will initially be used mainly to extend the capacity of existing mills.

*Miscellaneous measures.* A large number of other measures are available that can be taken in the iron and steel industry. In Table 2.7 they are grouped according to the investment costs. The fuel savings in the low cost range (average costs € 15/GJ saved annually) total to 1.0 GJ/tonne steel and the electricity savings to 0.1 GJ/tonne steel. In the high cost range (average costs € 50/GJ saved annually) the potential saving on electricity demand is 0.05 GJ/tonne steel. The savings on fuel demand in this range amount to 1.0 GJ/tonne steel.

**Table 2.7. Overview of miscellaneous measures. Between brackets the saving on fuel (f) or electricity (e) as GJ/tls is given with its source in the superscript. Savings are often based on one case and should be regarded as indicative only.**

Less than 25/GJ saved annually	More than 25 /GJ saved annually
Sinter and pellet plants:	Sinter and pellet plants:
- Reduction of air leakage (f: 0.01 <sup>1</sup> )	
- Improved process control (f: 0.01 <sup>1</sup> )	
Coke ovens:	Coke ovens:
- coke oven aspiration (f: 0.02 <sup>2</sup> )	- recovery of the sensible heat of coke oven by-product gas (f: 0.12 <sup>2</sup> )
- fuel gas preheating (f: 0.01 <sup>2</sup> )	- recovery of the sensible heat of waste gas (f: 0.04 <sup>2</sup> )
- programmed heating (f: 0.05 <sup>1</sup> )	- coil moisture control (f: 0.09 <sup>1,2</sup> )
Blast furnace:	Blast furnace:
- oxygen enrichment of combustion air for stoves (N/A <sup>3</sup> )	- heat recovery from hot stove waste gas (f: 0.1 <sup>2</sup> )
- cold blast main insulation (f: <0.01 <sup>2</sup> )	- heat recovery from slag (N/A <sup>2</sup> )
- improving blower efficiency (coupled with cogeneration) (N/A <sup>2</sup> )	- hot blast stove automation (f: 0.33 <sup>1</sup> )
- improved blast furnace control systems (f: 0.36 <sup>1</sup> )	
Basic oxygen furnace	Basic oxygen furnace:
- vessel bottom stirring (f: 0.01 <sup>2</sup> )	- dry gas cleaning (f: 0.92 (?) <sup>1</sup> )
- programmed ladle heating (N/A <sup>2</sup> )	- variable speed drives on fans (e: 0.01 <sup>1</sup> )
Electric arc furnace:	Electric arc furnace:
- bottom stirring (e: 0.07 <sup>1</sup> )	- ultra high power transformers (e: 0.06 <sup>1</sup> )
- hot metal charging (e: 0.03 <sup>2</sup> )	- energy efficient drive systems (e: 0.01 <sup>1</sup> )
- efficient secondary refining (N/A <sup>3</sup> )	- waste heat recovery on caster cooling water (f: 0.03 <sup>1</sup> )
Casting	
- efficient ladle preheating (f: 0.02 <sup>1</sup> )	
Rolling and finishing:	Rolling and finishing:
- hot charging and direct rolling (f: 0.52 <sup>1</sup> )	- insulation of furnaces (f: 0.14 <sup>1</sup> )
- process control in hot strip mill (f: 0.26 <sup>1</sup> )	- controlling oxygen levels and variable speed drives on combustion air fans (e: 0.29 <sup>1</sup> )
- reduce the unfired preheat zone (f: 0.01 <sup>2</sup> )	- energy efficient drives in hot rolling mill (e: 0.01 <sup>1</sup> )
- computer/combustion control modes (f: 0.01 <sup>2</sup> )	- waste heat recovery from cooling water (f: 0.03 <sup>1</sup> )
- scheduled free rolling (N/A <sup>2</sup> )	
Overall measures	
- Good housekeeping (N/A)	
- Preventative maintenance (f: 0.43 e: 0.02 <sup>1</sup> )	

<sup>1</sup>[Worrell *et al*, 1999]; <sup>2</sup>[AISI, 1998]

*Integrated mills – new capacity* – According to the baseline scenario no new capacity for integrated mills is expected in most Member States. An important exception is Finland, with an growth of production by 45% between 1990 and 2010. The best practice SEC is 18 GJ/tonne crude steel.

*Electric arc furnaces – new capacity* – A strong growth of steel production by electric arc furnaces is expected in the baseline scenario for nearly all Member States.<sup>16</sup> This steel will partially replace steel made in integrated mills. The best practice SEC for fuel is 0.94 GJ/tonne crude steel and for electricity 1.1 GJ/tonne crude steel [Phylipsen *et al.*, 2000].

<sup>16</sup> According to EISA is the growth of EAF in EU countries purely theoretical and impossible to foresee in the experts' opinion considering the important link between ferrous scrap availability and this technology, even if the use of substitute raw material is developed.

## 2.4 NON-FERRO METAL INDUSTRY

### 2.4.1 Aluminium industries

#### 2.4.1.1 Key parameters

The aluminium industry is characterised by four stages:

1. the mining of bauxite ore;
2. the refining from bauxite to alumina;
3. the production of aluminium from alumina (primary production) or recycled scrap (secondary production);
4. the casting of molten aluminium into semi-finished products.

The production of primary aluminium is the most energy-intensive step, requiring 15.5 MWh/tonne of aluminium (1997 figure for Europe [IPAI, 1999]). It is produced by passing a direct current through a bath with alumina dissolved in a molten cryolite electrodes. Here we will only deal with primary aluminium production.

Table 2.8 gives an overview of the production of primary aluminium in 1990 in EU Member States. Primary aluminium is produced in at least 7 Member States. Germany is by far the largest producer.

Table 2.8. *Production of primary aluminium in EU countries in 1990 [Nordheim, 2000].*

thousand tonnes of primary aluminium															
AUT	BEL	DEU <sup>†</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
89	0	727	0	353	0	296	303	150	0	226	0	272	0	97	2416

<sup>†</sup>FRG only



Figure 2.2. Location of primary aluminium production sites and company names in Europe, situation 1997 (only members of IPAI are shown)

Source: [www.world-aluminium.org](http://www.world-aluminium.org), the website of International Primary Aluminium Institute. Note that the site in Venhon (France) does not produce aluminium anymore. Not shown on this map are: Kubikenborg in Sundsvall (Sweden), Aluminium Essen (Germany) and Nordural, near Reykjavik (Iceland) [Nordheim, 2000].

#### 2.4.1.2 Options to improve the energy efficiency

*Retrofit existing Hall-Héroult process* - A portfolio of options to retrofit existing cells is available, e.g. alumina point-feeding, process computer control, conversion from wet to dry anodes (Soderberg cells only) and improvements to bath chemistry, anode design, busbar design and cathode shell composition and design [ICF, 1999]. An existing SWPB smelter being converted to PFPB can achieve at most a saving of 1 MWh/tonne depending on the starting point. A VSS smelter being retrofitted can also save about 1 MWh/tonne and a VSS smelter being rebuilt to PFPB can save 2 – 2.5 MWh/tonne. On an EU scale most of the smelters are already today operating PFPB technology and the smelters available for retrofitting are only about a third of the total operating EU smelters [Nordheim, 2000]. An average saving of 1 MWh/tonne for 33% of the capacity is assumed. Costs for such a retrofit are in the range of € 50-335/GJ saved annually, depending on the type of process [Nordheim, 2000]. We use an average value of € 192.50/GJ saved annually.

*Inert anodes* – Inert anodes are non-carbon anodes that are not consumed in the electrolytic process. Inert anodes are not yet commercially available, but field testing is currently underway [ICF, 1999]. Considering the potential savings, a direct replacement will not give any energy savings; this will require a total rebuilding of today's cell design, using a bipolar design. It is too optimistic to expect any saving already by 2010.

*Wettable cathode* – The wettable cathode is made of an inert material and allows reduction of the gap between anode and cathode [ICF, 1999]. Application of the wettable cathode can result in a reduction of the SEC, an increase of the current efficiency and an increase of the cell's stability. The wettable cathode has been field-tested and is undergoing materials failure analysis. Commercial designs are expected in the next 10-20 years. In combination with a drained cathode this could give energy savings of 0.2-0.3 MWh/tonne at any given plant, representing a saving of up to 2% on today consumption. The cost for this is difficult to estimate, but would require rebuilding of the cathode and additional equipment. The investment could be in the order of € 500 annual tonne, or € 550/GJ of electricity saved. This will not necessarily give any maintenance savings.

*Primary aluminium – new capacity* – No growth in the production of primary aluminium is considered in the baseline scenario of PRIMES [1999].

#### **2.4.2 Other non-ferrous metals industries**

Other non-ferrous metals produced in the EU are Copper, Zinc, Lead, Nickel, Cobalt and precious metals [EC, 1993]. Since the production volumes of these metals are far less than of aluminium they will not be dealt with separately. Measures to improve the energy efficiency of the production processes are known to be available but are not identified here. We estimate a saving of 25% on fuel demand and of 25% on electricity demand (1.1% a year). Investment costs are estimated at € 40/GJ saved annually and operation and maintenance costs at € 0.2/GJ saved annually<sup>17</sup>.

### **2.5 CHEMICAL INDUSTRY<sup>18</sup>**

The chemical industry consists of the production of agrochemicals, petrochemicals, inorganic chemicals and other chemicals, like pharmaceuticals and fibres. The most energy-intensive processes are the production of ammonia, which is the raw material for most fertilisers, the cracking of naphtha to produce ethylene and propylene, which are important building blocks in the petrochemical industry, and the production of chlorine. Table 2.9 gives a subdivision

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<sup>17</sup> According to Eurometaux these saving potentials are unrealistic.

<sup>18</sup> Emission of N<sub>2</sub>O from adipic acid and nitric acid production are treated in a separated part of this report (see page 54)

of the final energy consumption of the chemical industry in EU Member States as reported by Primes [1999] into four product groups. The energy consumption for the production of ammonia, petrochemicals and chlorine is based on the specific energy consumption for these products and the production for each country. The energy consumption for the group other chemicals is obtained by subtracting the energy consumption of the first three product groups from the total energy consumption of the chemical industry in that country. Details on specific energy consumption and production volumes are given in the next sections. As can be seen from the (negative) figures for other chemicals in Austria and Belgium there is a mismatch between the data obtained via the bottom-up approach as used here and the aggregated data from Primes [Primes, 1999]. This indicates that there is an uncertainty in this subdivision of about 20%. A closer examination of the data is required to reduce this uncertainty.

Table 2.9. Subdivision of the final energy consumption of the chemical industry in EU Member States into product groups valid for 1990<sup>2</sup>.

PJ	Ammonia		Petrochemicals		Chlorine/Alkali		Other Chemicals	
	Fuels	Electricity <sup>1</sup>	Fuels	Electricity <sup>1</sup>	Fuels	Electricity	Fuels	Electricity
Austria	4.6	0.0	9.9	0.0	0.0	0.0	-2.8	12.1
Belgium	8.4	0.0	55.5	0.0	0.8	7.5	-6.9	28.6
Germany	23.3	0.0	139.7	0.0	3.7	37.2	282.5	209.1
Danmark	0.0	0.0	0.0	0.0	0.0	0.3	7.1	4.9
Spain	3.4	0.0	38.8	0.0	0.7	7.0	50.7	14.8
Finland	0.0	0.0	8.3	0.0	0.3	3.2	2.0	14.3
France	23.7	0.0	91.2	0.0	1.6	16.2	26.8	99.6
UK	15.4	0.0	72.8	0.0	2.1	20.7	22.5	43.8
Greece	3.3	0.0	0.6	0.0	0.0	0.4	2.6	5.0
Ireland	3.8	0.0	0.0	0.0	0.0	0.0	3.2	3.0
Italy	18.5	0.0	56.7	0.0	1.4	13.7	136.5	81.3
Netherlands	34.7	0.0	82.2	0.0	0.7	7.3	53.1	46.6
Portugal	0.0	0.0	9.6	0.0	0.1	1.0	0.4	5.7
Sweden	0.0	0.0	11.6	0.0	0.3	3.2	23.3	14.1
<b>EU</b>	<b>139.1</b>	<b>0.0</b>	<b>577.1</b>	<b>0.0</b>	<b>11.8</b>	<b>117.6</b>	<b>600.8</b>	<b>582.8</b>

<sup>1</sup> It is assumed that all electricity consumed in the ammonia and petrochemicals industry is generated on-site; <sup>2</sup> Note that the energy consumption for the production of petrochemicals is for liquid cracking only. This means that about 8% of ethane-based production is excluded (mainly in the United Kingdom) [Worrell et al., 2000].

## 2.5.1 Fertiliser industry

### 2.5.1.1 Key parameters

The most energy intensive process in the fertiliser production is the synthesis of ammonia. In 1994 the total production of ammonia in the EU member countries amounted about 11 million tonnes per year. Around 50 plants were in operation, located in 11 countries. Details are given in Table 2.10, based on [EC,

1997]. Three types of production processes for the production of ammonia are currently in use in Europe:

1. Steam reforming of natural gas or other light hydrocarbons;
2. Partial oxidation of heavy fuel oil or vacuum residue;
3. Based on H<sub>2</sub> and N<sub>2</sub> rich streams from other processes.

Table 2.10. Ammonia production and number of plants in EU member countries (1992)<sup>19</sup> [EC, 1997]

AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX <sup>2</sup>	NLD	PRT	SWE	EU
ammonia production (million tonnes of N) (1992)															
0.35	0.50	1.78	N/A	0.48	N/A	1.41	0.87	0.14	0.38	1.10	-	2.67	N/A	N/A	9.69
Number of plants															
1	2	8	N/A	3	N/A	7	6	2	1	6	-	6	1	N/A	43

<sup>1</sup> FRG only; <sup>2</sup> Data for Luxembourg are included in the data for Belgium.

The first route is predominant in Europe. Only four plants (2 in Germany, 1 in Greece and 1 in Portugal) use partial oxidation and 3 plants use H<sub>2</sub> and/or N<sub>2</sub> rich streams from other sources (1 in France (uses also uses natural gas), 1 in Spain and 1 in United Kingdom) [EC, 1997].

The best achieved specific energy consumption for producing ammonia by steam reforming of natural gas is 28 GJ/ton NH<sub>3</sub> [EC, 1997]. The average value is 35-40 GJ/ton NH<sub>3</sub>. The best achieved specific energy consumption for partial oxidation process of heavy hydrocarbons is 38 GJ/ton NH<sub>3</sub> [EC, 1997]. The average value is 40-45 GJ/ton NH<sub>3</sub>. These values include the use of energy carriers as feedstock (21 GJ/ton NH<sub>3</sub>).

Table 2.11 gives SECs for the production of ammonia in the European Member States. Data are valid for 1995, except for the SEC for Germany that is for 1990 [PSI, 1998]. Data for 1990 were not available.

Table 2.11. Specific energy consumption of ammonia production, including feedstock energy (1995)<sup>20</sup> [PSI, 1998].

Specific energy consumption (GJ/ton NH <sub>3</sub> )															
AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	
34.1	37.8	34.1	-	28.1	-	37.8	38.7	44.5	31.0	37.8	-	34.0	44.0	-	

<sup>1</sup> FRG only

### 2.5.1.2 Options to improve the energy efficiency

*Process integration* – Better integration of heat exchangers and cogeneration of heat and power as well as other adaptations to the process can result in an improvement of the SEC of 3-4 GJ/ton NH<sub>3</sub> at maximum [De Beer *et al.*, 1994].

<sup>19</sup> Data for 1990 were not available; 1992 is the earliest year data on ammonia plants are collected on EU level.

<sup>20</sup> Data on 1990 were not available

Analysis of the process by pinch analysis is a useful tool to identify the options. Costs for implementation are estimated at € 10/GJ saved annually [De Beer *et al.*, 1994].

*Advanced reformer* – The largest losses in an ammonia plant based on steam reforming occur in the primary reformer. At least two ways are available to reduce these losses. One way relies on reducing the duty of the primary reformer, either by shifting part of the duty to the secondary reformer or by installing an adiabatic pre-reformer. Another way is to make more efficient use of the heat generated in the secondary reformer by heat exchange with the feed for the primary reformer. Most ammonia plant suppliers have developed a new process scheme based on reducing the losses in the primary reformer. The energy loss in the reformer section can be reduced by 3-5 GJ/ton NH<sub>3</sub> [De Beer, 1998]. Investment costs are estimated at € 65/GJ saved annually.

*Efficient CO<sub>2</sub>-removal* – The removal of CO<sub>2</sub> from the synthesis gas stream is normally based on scrubbing with a solvent. A reduction of the energy requirement for recycling and regeneration of the solvent can be achieved by using advanced solvents, pressure swing absorption or membranes. The type of removal process depends on the lay-out of the ammonia plant and on the requirements posed on the CO<sub>2</sub>, e.g. purity. Energy savings are in the order of 1 GJ/ton NH<sub>3</sub> [EC, 1997]. Investment costs are estimated at 15 €/GJ saved annually.

*Low pressure ammonia synthesis* – A lower ammonia synthesis pressure reduces the requirement for compression power, but also reduces the production yield. Less ammonia can be cooled out using cooling water so more refrigeration power is required. The recycling power increases also, because larger gas volumes have to be handled. The overall reduction on the energy demand depends on the situation and varies from 0-0.5 GJ/ton NH<sub>3</sub>. Another type of catalyst is required to achieve the lower synthesis pressure. Furthermore, adjustments have to be made to the power system and the recycle loop. Investment costs are estimated at € 25/GJ saved annually and operation and maintenance costs increase by € 1/GJ saved annually.

*Ammonia – new capacity* - In the baseline scenario of the PRIMES model a growth in fertiliser production is considered for most Member States<sup>21</sup>. It is assumed that the ammonia production will grow at the same rate as the whole fertiliser industry. Best practice SEC is 28 GJ/tonne [De Beer *et al.*, 1998].

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<sup>21</sup> Comment by VCI: the opposite is expected for Germany

## 2.5.2 Petrochemical industry

### 2.5.2.1 Key parameters

In Europe the petrochemical industry is mainly based on cracking of naphtha and gas oil (except for the United Kingdom) and the subsequent fractionation into small chemicals like ethylene, propylene, butadiene and aromatics. At the end of 1998 about 50 steam crackers were in operation in Western Europe. The total annual capacity was about 20.5 million tonnes of ethylene [CEFIC, 1999]. See Table 2.12.

Table 2.12. Annual capacity and number of steam crackers in EU member countries in 1998 (kt of ethylene)<sup>22</sup> [CEFIC, 1999]

AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
Annual production capacity (kt of ethylene)															
345	1870	4995	0	1410	290	3185	2535	20	0	2060	0	2950	350	405	20415
Number of crackers															
1	4	12	0	3	1	9	4	1	0	5	0	5	1	1	47

Table 2.13. Specific energy consumption of the petrochemical industry (for liquid crackers, GJ/tonne of ethylene) (1995).<sup>23</sup> For comparison, also the specific energy consumption per tonne of high value chemicals is shown, which takes better into account the differences in product mix between countries and, therefore, is a better indicator of energy efficiency. Source [Phylipsen et al, 1998; Groenberg et al, 1999].

Specific energy consumption															
Top row: GJ/tonne of ethylene															
Bottom row: GJ/tonne of high value chemicals															
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
33.8	34.9	32.3	-	32.4	33.8	33.7	33.8	33.3 <sup>1</sup>	-	32.4	-	33.6	32.4	33.8	33.3
18.2	18.9	16.4	-	16.6	18.2	17.3	18.2	17.0	-	16.6	-	16.5	16.6	18.2	17.0

<sup>1</sup> EU average

Table 2.13 gives the SEC of the petrochemical industry in EU Member States. The method to determine the SEC is described by Phylipsen *et al.* [1995; Phylipsen, 2000]. No differentiation can be made into fuel and electricity. It is assumed that electricity is generated in-house. Savings on the electricity demand are recalculated to savings on the fuel demand.

### 2.5.2.2 Options to improve the energy efficiency

*Miscellaneous* - Relatively simple measures such as the use computer controls, the monitoring of process conditions, reduced flaring, improved insulation, energy accounting and the use of chemicals to limit coking are estimated to result

<sup>22</sup> 1990 data will be made available by CEFIC

<sup>23</sup> Data for 1990 were not available.

in energy savings of 7-10% (2.8 GJ/tonne ethylene on average)<sup>24</sup> [Worrell *et al.*, 1994; Caddet, 2000; de Beer *et al.*, 1994]. Payback period is estimated to be below 2 years for the Netherlands and other European countries. This equals to about € 10/GJ.

*Process integration* – Optimised design of the heat exchanger network, e.g. by applying pinch analysis, can result in savings on fuel demand. The potential savings depend strongly on the plant lay-out and what has already been done in this field. Most large chemical companies performed pinch analyses years ago. Energy savings on the order of 5-15% were revealed [De Beer *et al.*, 1994]. However, not all proposed measures have been taken. The reasons were that the measures were too costly and that it was not considered core business at that time<sup>25</sup>. We assume that on average savings of 5% (1.5 GJ/tonne of ethylene) are still possible by process integration. Since the cheapest measures have probably already been taken, we assume a mid cost range of € 20/GJ saved annually.

*Gas turbine integration* - In a conventional cracker the furnace burners use combustion air to provide the oxygen to burn fuels. In case of gas turbine integration, combustion air is replaced by the off-gases of the gas turbine, with an oxygen content of 15-17% and a temperature of 500°C. This has been done in Asia and South Africa, where the higher energy costs justify the costs of the gas turbine system. Resulting energy savings amount to 1.8 GJ/t ethylene for ethane cracking, 2.9 GJ/t for naphtha cracking and 3.3 GJ/t for gas oil cracking. Since most crackers in Europe are naphtha crackers we use 2.9 GJ/tonne of ethylene [Albano and Olszewski, 1992]. Gas turbine integration increases the investment costs of a conventional cracker with about € 40/tonne of ethylene capacity [Albano and Olszewski, 1992]. Steam crackers with gas turbine integration are currently being commercially available from ABB Lummus [HP, 1997]. At current energy prices, though, they are generally not considered an economical option [Solomon, 1995]. The maximum penetration is therefore set at 5% of the fuel consumption in 2010.<sup>26</sup>

*Debottlenecking* – The efficiency and yield of a plant is often constrained by one process. Improving this process, e.g. by increasing the throughput, can result in a leap in performance of the total process. Debottlenecking is usually performed during the regular maintenance activities. No data on the potential for energy-efficiency improvement are available. We assume that the SEC of a

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<sup>24</sup> One expert commented that that most simple measures have been taken in the period 1975-1985, that the savings that are expected from process controls are not achieved in practice and that energy accounting does not improve the energy efficiency as such. According to this expert miscellaneous measures account for less than 1% improvement at best.

<sup>25</sup> One expert commented that there is a lot more than the investments: increase complexity, more difficult operation, more complex control, connecting streams that if a tube failure happens unsafe situations occur, plant reliability, maintenance costs. The assumption of average savings of 5% is probably on the high side, according to this expert.

<sup>26</sup> One expert states that the expected savings with this measure are too high.

petrochemical complex might be improved by 1-1.5 GJ/tonne ethylene by debottlenecking<sup>27</sup>. Investment costs are estimated at € 10/GJ saved annually.

*Cracking furnace* – The ethylene yield of the cracking furnace can be increased by using highly selective radiant coils [Merz and Zimmerman, 1992], conductive ceramics [Broutin and Busson, 1989; LANL, 1996] or high-pressure combustion [Vencken, 1990]<sup>28</sup>. On average the ethylene yield can be improved by 3-4%, resulting in a decrease of the production of by-products.<sup>29</sup> Other options to improve the efficiency of the cracking furnace are insulation of piping and ducting and using chemicals to decrease coking [Burns, 1991]<sup>30</sup>. An overall saving of 4% (1.3 GJ/tonne of ethylene) is assumed. Investment costs for these measures are € 40/GJ saved annually. Important positive side effects are expected such as an increased ethylene yield and a longer run time for the furnaces.

*Fractionation* – The gases that leave the cracking furnace are quickly chilled (quenched) and fractionated into products. Fractionation is done by distillation at very low temperature and high pressure. A number of measures can be taken to decrease energy consumption in the fractionation section.

- Refineries and chemical industries often over-reflux their distillation columns in order to ensure that product purification specifications are met [OIT, 1997]. According to the US Office of Industrial Technologies 30-50% more energy is used than necessary. It is estimated that an average reduction of energy consumption for distillation of 15% is attainable (or can be obtained by the application of better distillation controls [OIT, 1997]). The required combination of software and controls is fully developed (see e.g. [CFPA, 1998]).
- In conventional distillation ethylene (amongst others) is used as refrigerant. By replacing the ethylene refrigerant by a multi-component refrigerant, the refrigeration work would be divided in different steps (at different temperature levels), creating a system with a higher number of stages. As a result refrigeration energy consumption can be reduced with 3-7 % compared to efficient conventional systems [Saikh, 1996]. Capital costs can also be reduced because less compressor power is required.
- The distillation sequence varies by plant. The order in which the various products are separated from the process stream determines the number of separation steps required (i.e. capital costs) and energy requirement. Analyses have shown that an optimal distillation sequence can reduce distillation

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<sup>27</sup> One expert commented that there are plants debottleneckings that do not improve the energy efficiency at all.

<sup>28</sup> According to one expert these options are highly theoretical.

<sup>29</sup> VCI commented that the advantage of the more expensive naphtha crackers in comparison with ethane splitting lies in the simultaneous availability of propylene. With the demand for propylene increasing more considerably at the moment, a one-sided concentration on increasing the ethylene yield serves little purpose

<sup>30</sup> Use of chemicals to prevent coking was unknown to one of the experts.

energy requirements with 8% compared to conventional sequences with comparable investment costs [Zeppfeld et al., 1993].

- The fractionation can be made more efficient by using advanced recovery systems, such as Stone & Webster's dephlegmator-based ARS technology [Bowen, 1992]. Total plant energy requirement can be reduced by up to 5% relative to conventional designs. Investment costs of new plants can be significantly lower compared to conventional fractionation trains. In revamp situations the throughput of the fractionation can be increased by 40% for existing plants [Bowen, 1992]. However, since this is already (partially) accounted for at the option 'debottlenecking', we will not consider this here. For new plants capacity increase can be up to 70%, at a 10% lower capital costs, with a reduction in the specific energy consumption of 10% [Bowen et al, 1992; Chemical Week, 1992; HP, 1995; Stone & Webster, 1998]
- Fractionation can also be improved by using heat pumps, especially mechanical vapour recompression (MVR), instead of the conventional condenser-reboiler unit. MVRs have been, amongst others, successfully implemented in propane/propylene splitters at Sunoco's Markus Hook Refinery in Philadelphia (in 1998) [Sunoco, 1998] and at Shell's petrochemical plant in the Netherlands [Worrell et al., 1997]. Berghmans [1992] determined that 4% of the fuel demand in the petrochemical industry is used for separation processes that can be replaced by MVR, taking into account implementation obstacles. Steam is still required for start up and power is required for driving the pumps. An overall saving of 2% (0.5 GJ/tonne of ethylene) results. Investment costs are € 25/GJ saved annually [Meilli, 1990].

Large potentials for energy savings in the fractionation section are suggested. However, part of these potentials overlap, and part will not be implemented (yet by 2010) for a variety of reasons. Therefore, we estimate total energy saving attainable by improving fractionation at 1.5 GJ/tonne of ethylene against costs of € 25/GJ saved annually<sup>31</sup>.

*Petrochemicals – new capacity* – In the baseline scenario of PRIMES [1999] the production of petrochemicals will grow in the period 1990 – 2010 by the percentages given in Table 2.14. See section 2.2 for more details.

Table 2.14. *Baseline growth of production of petrochemicals in the period 1990-2010 [PRIMES, 1999].*

															% of 2010 production				
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE					
9%	23%	10%	0%	19%	16%	11%	12%	43%	59%	12%	23%	23%	17%	2%					

The best practice SEC depends on the product mix and is given in Table 2.15 [Phylipsen, 2000].

<sup>31</sup> One expert commented that the energy savings are relative to the fractionation part of a naphtha cracker considerable.

Table 2.15. Best practice specific energy consumption for petrochemical plants in 1995 [Phylipsen, 2000]<sup>32</sup>.

GJ/tonne ethylene														
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
22.3	22.3	23.1	N/A	23.1	20.8	22.3	20.8	23.1	N/A	23.1	N/A	22.4	23.1	20.8

### 2.5.3 Other chemicals

Chlorine and alkali. Chlorine and alkali are produced by electrolysis of brine. Three different types of electrolysis processes are in operation: using a mercury flow, a diaphragm or an ion-selective membrane. Table 2.16 shows that the mercury cell is the most common in the EU.

Table 2.16. Production and shares of different types of electrolysis cells used in a number of EU Member States in 1995 [Phylipsen et al., 1998]. The category 'unknown' comprises the capacity for which it is not known which of the three process types are used.

Country	Production capacity (kt of chlorine /year)	Process share (%)				
		Membrane	Diaphragm	Mercury	Other	Unknown or unspecified
Austria	0	0	0	0	0	0
Belgium	751	0	34	39	0	27
Germany	3719	4	4	42	0	50
Denmark	25	0	0	100	0	0
Spain	701	0	0	73	0	27
Finland	315	24	0	76	0	0
France	1617	17	15	46	1	21
Greece	35	0	0	100	0	0
Ireland	4	100	0	0	0	0
Italy	1374	6	0	70	2	21
Netherlands	729	54	18	28	0	0
Portugal	102	0	0	44	0	56
Sweden	318	32	0	68	0	0
United Kingdom	2068	4	11	35	2	48
<b>EU</b>	<b>11758</b>	<b>10</b>	<b>6</b>	<b>47</b>	<b>1</b>	<b>36</b>

Electricity consumption for mercury cells is approximately 11 GJ/tonne chlorine, whereas for the other cell types it is 9.5-10.0 GJ/tonne [Phylipsen *et al.*,

<sup>32</sup> One expert remarked that the values presented in this table indicate an unrealistic decrease compared to the values in Table 2.13.

1998]. The electricity consumption for chlorine and alkaline production in the EU Member States is estimated at 118 PJ (17% of the total electricity consumption of the sector 'chemicals'). The fuel consumption for chlorine and alkaline production in the EU Member States is estimated at 12 PJ (1 % of the total fuel consumption of the sector 'chemicals').

*Replacement of mercury by membrane cells* - The electricity demand of membrane and diaphragm cells is about 0.8-1.3 GJ/tonne chlorine lower than that of mercury cells [De Beer *et al*, 1994]. On the other hand, the heat demand for concentration of the alkali is about 0.5-1.0 GJ/tonne higher [Phylipsen *et al.*, 1995]. Concentration of alkali is not always necessary. Nevertheless, we assume an increase in fuel demand of 0.75 GJ/tonne on average. Investment costs are on the order of € 650/GJ saved annually if full investments are taken into account. However, if it is assumed that the average life time of a chlorine plant is 50 years, 40% of the mercury plants have to be replaced in the period 1990-2010 because they are at the end of their lifetime. For these plants zero additional investment costs are assumed. Per country, the degree of maximum implementation in 2010 is therefore assumed to be 40% times the current share of the mercury process.

Miscellaneous measures – A range of other measures to improve the energy efficiency of other chemicals can be applied. Examples of generic measures are:

- adjustable speed drives
- energy efficient motors and appliances
- optimising pressurised air systems by reducing leakages, splitting the systems into several pressure levels and lowering the pressure for certain applications
- improved lighting
- more efficient separation processes
- improved reactor design
- more efficient burners
- optimise heat exchanger networks
- application of heat pumps

We divide the measure into two tranches:

Tranche 1: Low costs: fuel 5%; electricity 15%; € 25/GJ saved annually; O&M € 0.1 GJ saved annually.

Tranche 2: High costs: fuel 10%; electricity 10%; € 50/GJ saved annually; O&M € 0.2 GJ saved annually.

## **2.6 NON-METALLIC MINERALS**

The most important building materials, both in terms of production and of energy intensity, are cement and concrete, glass and ceramics.

Total EU fuel consumption in this sector was 1280 PJ and the electricity demand was 244 PJ in 1990 [PRIMES, 1999].

## 2.6.1 Cement and concrete

### 2.6.1.1 Key parameters

Table 2.17 gives an overview of the production of cement in EU Member States. Italy is by far the largest producer, followed by Germany, Spain and France. Per capita, Luxembourg is the largest cement consumer (1079 kg per capita). This is nearly 5 times as much as in the United Kingdom (232 kg per capita) [EC, 1993].

Table 2.17. Production of cement in EU Member States in 1990 and 1998 [Figures provided by Cembureau, sources [Cembureau, 1991; 2000]

		Production of cement (million tonnes)														
	AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
1990	4.9	6.9	27.7 <sup>1</sup>	1.2	28.7	1.7	27.0	13.9	13.4	1.8	40.8	1.3	3.4	7.3	2.4	182.5 <sup>2</sup>
1998	3.8	8.0	34.0	2.1	33.1	1.1	19.7	12.9	14.8	2.3	36.2	1.1	3.2	9.8	2.3	182.3 <sup>3</sup>

<sup>1</sup> Figure for Western Germany only; figure for the reunificated Germany estimated at 34.2;

<sup>2</sup> Figure for total EU15 cement production is not adjusted by intra-trade clinker;

<sup>3</sup> Figure for total EU15 cement production is adjusted by intra-trade clinker (2.1 Million tonnes)

Cement is produced in two steps: (1) the production of clinker, (2) mixing clinker with other compounds to cement. The production of clinker is the most energy-intensive step. It requires the calcination in a high-temperature kiln (1450 °C) of raw materials (clay, limestone, etc) previously prepared in paste or powder form depending on the production process (wet or dry). In 1995, about 78% of Europe's cement production is from dry process kilns, a further 16% is accounted for by semi-dry/semi-wet process kilns and about 6% stems from wet process kilns. The actual specific fuel demand of clinker production for different kiln types is given in Table 2.18.

Table 2.18. Actual specific fuel demand for different types of cement kilns [BREF-Cement, 2000].

Kiln type	Specific fuel use (GJ/tonne clinker)
Dry process, multi-stage cyclone preheater and precalciner kiln	About 3.0
Dry rotary kiln equipped with cyclone preheater	3.1-4.2
Semi-dry/semi-wet proces (Lepol-klin)	3.3-4.5
Dry process long kiln	up to 5.0
Wet process long kiln	5.0-6.0
(Shaft kiln)	(3.1-4.2)

Electricity is mainly required for raw and finish grinding and the exhaust fans. Total specific electricity production is in the order of 90-130 kWh/tonne cement (0.3-0.5 GJ/tonne) [BREF-Cement, 2000].

Important products are Portland cement (usually containing 90% clinker), Portland fly-ash cement (65-90% clinker) and blast furnace cement (5-65% clinker) [Hjorth, 2000]. The product mix strongly affects the specific energy consumption for cement production.

The specific fuel consumption of cement production in EU Member States is given in Table 2.19. The specific electricity consumption per country is not known. It is set at an average value of 110 kWh/tonne cement (0.4 GJ/tonne cement).

Table 2.19. Specific fuel consumption for cement production [Cembureau, 1991, 1998]

	Specific fuel consumption in GJ per tonne of clinker															
	AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
1990	3.48 <sup>3</sup>	- <sup>1</sup>	3.77 <sup>4</sup>	4.34	3.77	3.56	- <sup>1</sup>	4.60	- <sup>1</sup>	3.57	- <sup>1</sup>	3.42	- <sup>1</sup>	3.42	3.41	3.98 <sup>2</sup>
1996	3.55 <sup>3</sup>	4.26	3.52 <sup>4</sup>	4.36	3.49	3.56	- <sup>1</sup>	4.44	- <sup>1</sup>	- <sup>1</sup>	- <sup>1</sup>	3.67	- <sup>1</sup>	3.48	3.39	3.74 <sup>2</sup>

<sup>1</sup> Figures are not publishable

<sup>2</sup> Figures for total EU15 countries are weighted averages

<sup>3</sup> Figures derived by Cembureau from Austria "Hakl-Report"

<sup>4</sup> German figures derived by Cembureau from VDZ "CO<sub>2</sub>-Monitoring Report"

Since for many countries the figures are not publishable we use the average value for the total EU15. Using this average specific fuel consumption and the total EU cement production the EU fuel demand for cement production can be estimated at 600 PJ. Analogously, the EU electricity demand for cement production is estimated to be about 73 PJ.

### 2.6.1.2 Options to improve the energy efficiency

*The use of waste as replacement for fossil fuels* – Waste that is fed through the main burner is decomposed in the primary burner zone at temperatures of 2000°C. Waste fed to the secondary burner, preheater or precalciner is burnt at lower temperatures; sometimes too low to ensure decomposition of halogenated organic substances. Types of waste that are most frequently used as fuels in Europe today are: used tyres, rubber, paper waste, waste oils, waste woods, paper sludge, sewage sludge, plastics, spent solvents [BREF-cement, 2000].

Waste processing in the cement industries is technical and economical feasible and current practise. Waste as alternative fuel is increasingly used in cement plants. Waste may reduce CO<sub>2</sub> emissions by 0.1 to 0.5 kg/kg cement produced compared to current used production techniques using fossil fuels. The use of waste generates no additional emissions, although care should be taken for high volatile elements as mercury, thallium, cadmium and chlorine.<sup>33</sup> On the other

<sup>33</sup> The emissions of conventional air pollutants (including mercury, thallium, cadmium and chlorine) have been regulated under the new Waste Incineration Directive (2000/76/EC) dated 4 December 2000.

hand, the use of waste does not impair clear environmental advantages, besides the reduction of substituted fossil fuels [BREF-cement, 2000].

The European cement industry used about 25-35 PJ of alternative fuels in 1990, equalling about 3-5% of the primary energy consumption [Hendriks *et al.*, 1999]. In 2000 10-15% of the total fuel consumption in the EU was in the form of alternative fuels and the rate is constantly increasing [Hjorth, 2000]. The future possibility of using waste differs from country to country. The barriers are availability of suitable waste, lack of infrastructure to collect useful waste, legislation, public concern and competition with incinerators. According to Cem-bureau a realistic forecast for an EU average would be 17% substitution and a very optimistic value would be a 20% substitution by 2010. However, since these figures are based on all barriers and not just the technical barriers to implementation, the technical potential can be higher. We assume that in the period 2000-2010 the substitution of fossil fuel by waste continues at an average annual rate of 1.5% a year. According to this scenario the use of waste will account for 25% of the fuel input in the EU cement industry. No distinction is made to separate countries.

Since waste can be used as combustible in a variety of installations such as incinerators with or without energy generation, power plants and cement kilns, it seems very complicated to establish the avoided CO<sub>2</sub> emissions of one of the installations.

In order to evaluate the avoided CO<sub>2</sub> emissions by replacement of fossil fuel in cement kilns three processes are considered:

- By *placing waste in landfills*, CO<sub>2</sub> and CH<sub>4</sub> are emitted. As CH<sub>4</sub> has a global warming potential of 21, the greenhouse gas equivalents avoided by using waste in cement kilns are above 100%;
- By *burning waste in incinerators without energy generation*, the CO<sub>2</sub> emissions avoided by using waste in cement kilns are 100%<sup>34</sup>
- By *burning waste in incinerators with energy generation*, the CO<sub>2</sub> emissions avoided by using waste in cement kilns are below 100%.

Some of the materials (e.g. certain types of plastics waste) burned as fuel in cement kilns could be recycled. The production of new plastics or other products from recycled material would require less energy than if virgin material was used. The corresponding CO<sub>2</sub> emissions would be lower if materials were recycled. The three options described above should ideally also be compared with different recycling options (for Germany, see e.g. [Patel *et al.*, 1999]).

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<sup>34</sup> Note that the Waste Incineration Directive requires (Art. 6(6) that "any heat generated by the incineration or the co-incineration process shall be recovered as far as practicable". This requirement enters into force on for new plants at the end of 2002 and for existing plants at the end of 2005. Thus after 2005 incineration without energy recovery will no longer be allowed.

However, due to data constraints in many EU countries these issues were not analysed in this study.

To account for these factors correctly an analysis of, amongst others, waste availability is required. Here we assume, for the ease of calculation, that 100% of the CO<sub>2</sub> emission can be avoided by this option.

Costs associated with this option depend among others on the type of waste that is used. Costs for complex systems for automated tire feed are about € 3.5/tonne of clinker capacity [CADDET, 2000]. Less complex systems have lower costs: € 0.1-1.0/tonne of clinker capacity [Martin *et al.*, 1999]. The costs per GJ saved depend on the clinker/cement ratio and on the type of clinker kiln. Here we will use average investment costs of € 0.5/GJ of fossil fuel use avoided per year. No additional operation and maintenance costs are assumed.

*Reduce clinker content of cement* – Clinker production is the most energy-intensive step in cement production. Moreover, on average about 50% of the direct CO<sub>2</sub> emissions of cement production is the non-fuel related process emission from clinker production. Substantial CO<sub>2</sub> emission reduction can be obtained by reducing the amount of clinker required, i.e. reducing energy use and process emissions. One option to reduce clinker use is by substituting clinker by industrial by-products such as coal fly ash, blast furnace slag or pozzolanic materials (e.g. volcanic material). The relative importance of additive use can be expressed by the clinker/cement ratio to produce cement in a specific country. The clinker/cement ratios for some of the EU Member States in 1994 are given in Table 2.20.

Table 2.20. *Clinker/cement ratio in EU Member States in 1990 [EC, 1992]*

Clinker/cement ratio (%)															
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
N/A	66% <sup>1</sup>	83%	88%	78%	N/A	80%	84%	84%	94%	77%	N/A	N/A	86%	N/A	80%

<sup>1</sup>Figure provided by Cembureau

It should be noted that Cembureau has made an internal survey of clinker/cement ratios in EU Member States. Although these figures are known, they are not available for this study. Cembureau does confirm the average value of about 80% for the EU as a whole.

The potential for application of blended cements depends on the availability of blending materials and on standards and legislation. Furthermore, there is a market resistance against different types of cement and a lack of useful industrial by-products. We assume that the average clinker/cement ratio can be reduced to 75% in 2010. The associated CO<sub>2</sub> emission reduction is determined per Member State. Costs for shipping of the blending materials are balanced by the avoided costs for clinker production.

*Wet kilns* - Wet kilns use about twice as much fuel as dry kilns. Replacement of wet kilns by dry kilns therefore has the potential of improving the energy efficiency of cement production considerably. However, only 6% of the 1995 EU cement is produced in wet kilns. The choice for this process is usually dictated by the availability of raw materials. Conversion of the process is therefore not an option.

However, we assume a phase-out of wet kilns. An estimate of Cembureau is that in 2010 2-3% of the cement will be produced in wet kilns. The capacity that is taken out of operation should be met by dry processes. Costs will be in the range of € 55-100 per tonne of annual capacity. However, this phase-out of wet kilns will mainly happen for other reasons than energy savings. Therefore, no costs expressed in € per GJ energy saved are associated with this measure.<sup>35</sup> A further reduction of wet kiln processes is only possible at excessive costs and is not accounted for in the database.

*Application of multi-stage preheaters and pre-calciners* – An existing preheater kiln may be converted to a multi-stage preheater precalciner kiln by adding a precalciner and, when possible and extra cyclone. The addition of a precalciner will generally increase the capacity of the plant. For new plants the specific fuel consumption can be lowered; this is not automatically the case in retrofit situations [Hjorth, 2000]. The conversion of a plant in Italy, using the existing rotary kiln, led to a capacity increase of 80-100% (from 1000 tpd to 1800-2000 tpd), while reducing the energy use from 3.56 to 3.06-3.19 GJ/tonne clinker [Sauli, 1993]. Investment costs estimates range from € 8.5 [Vleuten, 1994] to € 28 [Jaccard and Willis, 1996] per tonne annual capacity. We assume average costs € 18.5/tonne clinker, or € 46/GJ saved annually<sup>36</sup>. Operation and maintenance costs decrease by € 2.5/GJ saved annually due to the expanded production capacity. Since this measure can only be applied to new plants, we assume only a small future penetration of 5% up to 2010.

*Optimisation of heat recovery in clinker cooling* - The clinker cooler cools clinker from 1200 °C down to 100 °C . The most common cooler designs are of the rotary, planetary (or satellite) and grate type. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner [Alsop and Post, 1995]. Grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd). Grate coolers use electric fans and excess air. Rotary coolers (used for approximately 5% of the world clinker capacity for plants up to 2000-4500 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3000-4000 tpd) do not need cooler fans and use little excess air, resulting in relatively lower heat losses [Buzzi and Sas-

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<sup>35</sup> Cembureau commented that phase-out of wet kilns mainly happens in order to reduce production costs by energy savings, and that therefore the costs associated with this measure should be considered and included.

<sup>36</sup> Cembureau indicated that these costs are too low for new plants. According to their information the costs would be 55-100 per tonne annual capacity for a new line (including raw material, preheater, precalciner and cooler).

sone, 1993; Vleuten, 1994]. Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Heat recovery can be improved through reduction of excess air volume [Alsop and Post, 1995], control of clinker bed depth and new grates [Buzzi and Sassone, 1993]. Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. In the EU-12, over 70% of the clinker coolers were grate coolers, the rest being mainly planetary coolers [CowiConsult, 1992].

Reported fuel savings are on the order of 0.04-0.15 GJ/tonne [Birch, 1990; Holderbank, 1993; COWIconsult, 1993]. We assume that the average technical saving potential is 0.1 GJ/tonne in the EU. The penetration in 1990 was 50%, the maximum technical penetration in 2010 is expected to be 100%. Investment costs are estimated at € 2/GJ saved annually [Martin *et al*, 1999]<sup>37</sup>.

*Electricity savings* – The demand for electricity can be reduced by various measures:

- Use roller mills for grinding raw materials instead of ball mills (saving 7 kWh/tonne clinker [Martin *et al*, 1999]).
- Efficient grinding technologies, high-pressure mills (saving 16-19 kWh/tonne [Hendriks *et al*, 1999])
- High-efficiency classifiers resulting in a sharper separation reducing over-grinding (saving 1.7-2.3 kWh/tonne [Hendriks *et al*, 1999]).
- High-efficiency motors and drives and adjustable speed drives (saving 10-15 kWh/tonne [Martin *et al*, 1999]).

Since these measures do not add up, the total potential saving is estimated at 10 kWh/tonne. Average costs are € 35/GJ saved annually [Martin *et al*, 1999].

*Cement – new capacity* – In the baseline scenario of PRIMES [1999] the production of cement will grow in the period 1990 – 2010 by the percentages given in Table 2.21<sup>38</sup>.

Table 2.21. *Baseline growth of production of cement in the period 1990-2010 [PRIMES, 1999].*

															% of 2010 production				
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE					
18%	17%	0%	0%	27%	2%	0%	0%	42%	17%	12%	17%	20%	25%	0%					

The best practice SEC depends on the clinker/cement ratio. We assume a clinker/cement ratio of 75%, equal to the measure ‘reduce clinker content of cement’ for existing capacity. The best practice value for this ratio is 2.3 GJ fuel/tonne of cement and 0.25 GJ electricity/tonne of cement [Phylipsen, 2000].

<sup>37</sup> Cembureau commented that investment costs are probably much higher. This was based on information from a demonstration project in Europe.

<sup>38</sup> It should be noted that Cembureau does not foresee an increase in production.

## 2.6.2 Other non-metallic minerals

### 2.6.2.1 Glass

The EU glass industry produced 29 million tonnes of glass in 1997, of which 17.5 million tonnes consisted of container glass and 6.9 million tonnes of flat glass [EC-JRC, 2000]. In 1990 the EU glass production was 22.5 million tonnes [EC, 1993].

The energy demand for glass production varies enormously depending on type of glass produced and furnace type. The SEC for container glass production is 6.5-9.0 GJ/tonne of which about 15% is for electricity [EC-JRC, 2000, Infomil, 1998]. For flat glass a range of 5.5-8.0 GJ/tonne for melting rate is reported by [EC-JRC, 2000]. However, the total process is often below 8 GJ/tonne [CPIV, 2000]. Infomil gives a value of 12 GJ/tonne [Infomil, 1998]. Based on SECs per type of glass, the energy demand for glass production in 1997 can be estimated to average 265 PJ for the whole EU [EC-JRC, 2000]. For 1990 the energy demand is estimated at 205 PJ pro rata to production volume.

About 75% of the energy is used for glass melting. Several types of melting furnaces are in operation, see Table 2.22. In this table, the average melting capacity does not reflect the widely diverse character of the glass industry where manufacturing techniques vary from the small 10 tonnes/day electrically heated furnaces for special glass to the cross-fired regenerative furnace in the flat glass sector, producing 700 tonnes per day.

Table 2.22. Different furnace types in EU [EC-JRC, 2000]

Type of furnace	Number of units	Melting capacity (million tonne/year)	Average melting capacity (tonne/day)
End-fired	265	13.1	135
Cross-fired	170	15.3	250
Electric	100	1.1	30
Oxygen	30	1.2	110
Others	335	4.3	35
<b>Total</b>	<b>900</b>	<b>35</b>	<b>110</b>

*Improved melting technique and furnace design* – The choice of melting technique can have a great effect on energy efficiency. The choice is largely determined by a range of economic considerations. The main factor is the desired production rate and the associated capital and operating cost over the life of the furnace. Regenerative furnaces are more efficient than recuperative furnaces due to the higher preheat temperature and the larger size of the furnace. Other types of furnaces, like electrical melting or oxy-fuel technology, allow to improve energy efficiency. However, power generation efficiency and distribution losses or energy required for oxygen production must be taken into consideration, resulting in a less clear CO<sub>2</sub> and energy balance. On each type of furnace,

depending on starting situation, there are some options to improve the efficiency of the unit. For instance, in regenerative furnaces [EC-JRC,2000] you may :

- Install multi-pass regenerators (energy saving up to 15%, but more generally 5-8%)
- Fusion cast corrugated cruciforms (typical fuel savings of 7%; 120 furnaces in EU)
- Insulation of regenerator structure (energy saving of about 5%)
- Install waste heat boilers (up to 15% of energy saving)

These savings are not additive and the penetration of these techniques in 1990 is not known. However, these techniques were already used where it was possible in 1990. We estimate that a 8% saving on fuel demand of regenerative furnaces on average is possible in the period 1990-2010. The fuel demand of regenerative furnaces is estimated on the basis of Table 2.22 at 75% of the total fuel demand of the EU glass industry. Investment costs are not known. However an estimate of €25/GJ saved is made.<sup>39</sup>

*Raising cullet percentage in raw materials* – Cullet is recycled glass. Internal cullet (recycled glass from the production line) has a higher quality than external cullet (recycled glass from consumer). Melting cullet requires less energy than melting raw materials because endothermic chemical reactions associated with glass formation have been completed and its mass is 20% lower than the equivalent batch materials. A rule of thumb is that each 10% of cullet substituted for raw materials results in 2.5-3.0% reduction in furnace energy consumption. Cullet use varies according to type of glass. For container glass cullet levels of more than 90% are found [Infomil, 1998]. The EU average is 48% (1996) [EC-JRC, 2000]; the value for 1990 is on average 41% [CPIV, 2000]. Variations between Countries are attributed to geographic and cultural differences more or less favourable for efficient post-consumer glass collection . Trade imbalance of bottled drinks, particularly wine, may also affect availability of suitable cullet for local container glass production. It is assumed that container glass can on average be made out of 70% cullet, with some variation between countries according to local condition. Indeed , 90% cullet can not be reached in all container furnaces because of restrictions on colour and quality[EC-JRC,2000]. An average energy saving of 8% is therefore achievable (compared to the 1996 EU-average). Costs are associated with the recycling schemes; these are not accounted to the glass industry, nor are the transport energy cost implied by logistical aspects of high recycling rates. A reduction in production costs can in some cases be achieved due to the possibility of an increased melting load.

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<sup>39</sup> Investment 1 million; saving 1 GJ/tonne; average furnace capacity 100 tonne/day.

*Batch and cullet preheating* – Waste heat can be used to preheat batch and cullet. Three types of preheaters are in use: direct, indirect and electrostatic/direct preheater. Energy savings of 10-20% have been reported [Infomil, 1998]. Associated advantages can be an increased capacity and furnace life. Disadvantages are that the emission of particulate matter and dioxins may increase and there may be some odour generation. Preheating of batch only is problematic. Preheaters can be installed at practically any furnace with enough (at least 50 to 60%) cullet in the batch [Infomil, 1998]. Investment costs for an electrostatic preheater were € 2.5 million for a 370 tonne/day plant [Infomil, 1998]. With energy savings of 0.8 GJ/tonne the specific investment costs can be calculated to be € 18/GJ saved annually. The electricity demand will increase by 0.02 GJ/tonne.

*Electricity savings* – Electricity is used for compressed air, mould cooling, electric boosting, water pumping and miscellaneous operations. Savings on the demand for electricity are possible by generic measures like adjustable speed drives, higher efficiency equipment, avoiding oversizing of equipment and reducing friction losses. Based on experience in other sectors the savings is estimated at 25% (0.35 GJ/tonne) at costs of €20/GJ saved annually<sup>40</sup>.

*New capacity* – Between 1990 and 2010 the capacity for primary glass production will expand in some EU Member States. The share of new capacity in total capacity is derived from PRIMES [Primes, 1999] and is given in Table 2.23.

Table 2.23. Share of new glass melting capacity in total primary glass production in 2010.<sup>41</sup>

AUT	BEL	DEU <sup>†</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
0%	0%	0%	0%	15%	0%	0%	16%	52%	27%	8%	0%	7%	46%	0%	10%

<sup>†</sup> FRG only

It is assumed that new glass melting plants can be built with a specific energy consumption of 6.5 GJ/tonne [ER-JRC, 2000].

### 2.6.2.2 Ceramics goods, bricks and roofing tiles

Ceramic products are produced in a number of heterogeneous industries: tiles for floors and walls, sanitary ware, tableware and ornamental ware, industrial ceramics and refractory products. The type of bricks and roof tiles used in Europe differs strongly between countries and even between regions.

To estimate the share for producing ceramic goods and bricks and roof tiles in EU energy demand we use the shares of this sector in the Netherlands: 35% of

<sup>40</sup> The Comité Permanent des Industries du Verre Européennes (CIPV) questions the saving potential of 25%. According to CIPV the glass industry has to face an increasing specific electricity consumption for auxiliaries. This additional electricity demand comes from further demands in downstream activities like decoration of products, environmental requirements (waste gas treatment, waste water pumping) and process automation requiring more control.

<sup>41</sup> CIPV does not agree with this table.

the fuel demand and 18% of the electricity demand of the sector building materials.

*Miscellaneous measures* – Due to the diversity of products we describe several measures that can be taken in the ceramic industry. We combine them into one measure with average savings and investments.

Roller kiln to replace tunnel kiln at sanitary ware production: At Koninklijke Sphinx in Maastricht, the Netherlands, sanitary stoneware is produced, like washbasins and toilet bowls. Here a new type of kiln was installed in 1988, consisting of a tunnel kiln with an integrated drying section, through which the products are transported on a line of ceramic rollers. The baking process time was reduced from 25 to 10 hours. The natural gas demand reduces from 10.8 GJ/tonne to 4.1 GJ/tonne. Additional investments were € 284,000, or € 6/GJ saved annually [Caddet, 2000].

Improving tunnel kiln for roof tiles production: Air leakage in a tunnel kiln has been reduced to almost zero by installing a water bed under the kiln at Koramic Narvik in the Netherlands. The baking time was reduced from 70 to 17 hours. Fuel savings are 1.9 GJ/tonne and electricity savings amounted to 0.09 GJ/tonne. Investments are € 25/GJ saved annually [Caddet, 2000].

Low-energy sintering machine: Instead of an autoclave for baking coloured tiles a sintering machine is used at Boral Doorwerth Straatsteen in the Netherlands. The energy consumption is reduced from 4 GJ per tonne to 2.5 GJ/tonne. Additional benefits are increased capacity and saving on staff costs. Pay back period is 2 years, or about € 7/GJ saved annually [Caddet, 2000]

Low thermal mass kiln wagons: The heat losses involved with heating the kiln wagons can be reduced by making the wagons of a material with a low thermal mass. Savings are estimated at 0.4 GJ/tonne and investment at € 25/GJ saved annually.

We assume that overall savings of 30% on fuel and 25% on electricity are possible in the ceramic industry<sup>42</sup>. Average investment costs are € 15/GJ saved annually.

*Ceramics – new capacity* – We assume that new plants that will be built in the period 1990-2010 can be 30% more efficient than the 1990 average.

### **2.6.2.3 Miscellaneous products**

Miscellaneous products include cement products, sand-lime stone, building stone and gypsum concrete.

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<sup>42</sup> The Cerame-Unie does not agree with these saving potentials. Tentatively, they feel that the specific energy consumption can be reduced at 15% at best.

*Miscellaneous products* – A range of other measures to improve the energy efficiency can be applied. Examples of are:

- adjustable speed drives
- energy efficient motors and appliances
- improved lighting
- more efficient separation process
- energy recuperation at ovens
- improved space heating systems
- optimise heat exchanger networks
- application of heat pumps

The savings add up to 30% of the fuel demand and 20% of the electricity demand [De Beer *et al.*, 1994]. Investment costs are estimated at € 15/GJ saved annually.

## 2.7 PULP AND PAPER INDUSTRY<sup>43</sup>

### 2.7.1 Key parameters

In 1990 the EU wood pulp production amounted to 31.2 million tonnes (see Table 2.24) and the paper and board production to 59.9 million tonnes (see Table 2.25) [FAO, 1998]. Sweden and Finland are the largest pulp producers. Germany is the largest paper producer.

Table 2.24. Wood pulp production in 1990 in EU Member States (excluding waste paper pulp) [FAO, 1999].

million tonnes															
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
wood pulp production															
1.5	0.5	3.0	0.1	1.6	8.9	2.4	0.7	0.1	0	0.6	-	0.2	1.5	10.2	31.2
of which chemical pulp															
1.2	0.2	1.4	0.1	1.4	5.6	1.7	0.1	0	0	1.7	-	0	1.5	7.3	20.9

Table 2.25. Paper and board production in 1990 in EU Member States [FAO, 1998].

million tonnes															
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
2.9	1.2	13.2	0.3	3.5	9.0	7.0	4.8	0.4	0	5.6	-	2.8	0.8	8.4	59.9

Paper is produced from two main materials, i.e. primary wood pulp and waste paper.

<sup>43</sup> The Confederation of European Paper Industries (CEPI) commented on a draft version of this section. There was not enough time to discuss their comments. Therefore, if the comments were clear they have been included in the text. Otherwise, the CEPI comments are shown in footnotes.

Wood pulp is made from fibers in wood. Two main processes can be distinguished: chemical pulping (also called kraft pulping) and (thermo-)mechanical pulping.

Chemical pulping relies on sulphur and sodium compounds to dissolve the lignin. However, nowadays sulphur free processes are also available. Chemical pulping requires a high energy input but are also steam and electricity producers by burning wood, bark and chemicals. Although the heat demand of chemical pulp mills can be in the order of 10-14 GJ/tonne, the excess heat is about 5 GJ/tonne [BREF-PP, 2000]. Usually this heat is used in the integrated paper mill. The electricity consumption is 400-750 kWh/tonne. All this electricity is in practice generated in the recovery station. In fact, there is an overproduction of electricity in the pulp mill [BREF-PP, 2000].

There are two main processes for mechanical pulping. In the ground wood processes (Stone Ground Wood (SGW) or Pressurised Ground Wood (PGW)) logs are pressed against a rotating grinding stone. In refining processes the wood chips are defiberized between disc refiners. Thermal-mechanical pulping (TMP) is a refining process in which the fibers are softened by heating.

The specific energy consumption varies per pulping process and depends to a large extent on the quality demands set on the pulp by the end product. EC [BREF-PP, 2000] reports electricity consumption that ranges from 1100-2300 kWh/tonne of pulp for ground wood processes. Heat produced during the process may be recovered as hot water (maximum 30% of electricity input) or as steam (maximum 20% at pressurised processes). The electricity consumption for refining processes is higher, ranging from 1600-3600 kWh/tonne of pulp. However, the recoverable energy may be as high as 65% of the electricity input. Heat is required only during the start-up phase.

In the EU about 45% of the fiber input for paper stems from recycled paper. Recovered paper figures per Member State are given in Table 2.26. Denmark and Ireland recover more paper than they need for their own paper production.

*Table 2.26. Share of recovered paper that is utilised in total paper production in 1998 (% utilised recovered paper/paper production) [CEPI, 1999]*

% utilisation of recovered paper/paper production															
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
43%	34%	61%	122%	81%	5%	54%	72%	76%	128%	50%	-	71%	31%	18%	45%

Waste paper needs to be cleaned and de-inked before it can be used. Then it is pulped and can be mixed with new fibers from wood pulp. The paper making process involves preparing the stock from pulp, forming a sheet, de-watering and drying, and sometimes coating the paper. The drying of paper is the step that consumes the highest amount of direct energy in the paper mill. It is done by leading the wet sheet of paper over steam-heated cylinders resulting in evaporation of the water in the sheet. The energy demand depends on the type

of paper that is produced and the efficiency of the machine and varies from 2.5-9.0 GJ of heat and 1.3-2.9 GJ of electricity per tonne paper [De Beer *et al.*, 1998]. Average values are 5.6 GJ of heat and 2.1 GJ of electricity per tonne of paper.

### 2.7.2 Options to improve the energy efficiency

*Super pressurised ground wood (mechanical pulp)* – Mechanical pulping is more energy-intensive than chemical pulping. However, replacement of mechanical pulping by chemical pulping is not a feasible option. Mechanical pulping uses the wood material more efficiently than kraft pulping. In addition, the manufacturing costs of mechanical pulp are significantly lower than of kraft pulp.

The energy demand for pressurised ground wood (PGW) pulp can be halved by grinding under elevated pressure (4.5 bar). Valmet-Tampella has developed a process called Pressure Ground Wood-Super process. As a result, higher temperatures can be achieved without boiling, softening the lignin [Caddet, 2000]. The strength properties of the produced pulp are close to those of TMP-pulp. According to Valmet-Tampella pulp produced in this process can replace TMP-pulp. The electricity consumption for this process is 1100-1300 kWh/tonne of pulp [Caddet, 2000], which is about 600 kWh/tonne less than for TMP.<sup>44</sup>

The pay-back time varies from 2-10 year. Benefits are not only obtained from reduced electricity consumption, but also from a reduction in the use of chemical pulp. Less chemical pulp (10-20%) is required to have a pulp mix with equal qualities. Since chemical pulp is less energy-intensive than mechanical pulp, this effect reduced the energy saving. The resulting saving is on average 2.5 GJ/tonne pulp.

Costs for system installations are estimated at € 220/tonne of pulp as well as a € 2.6/tonne saving for O&M-costs [Martin *et al.*, 2000].

On the basis of average specific energy consumption and data on physical production of pulp and paper the share of the electricity demand for mechanical pulping in the total electricity demand for pulp and paper making per EU Member State can be estimated, see Table 2.27.

Table 2.27. *Calculated share of electricity demand for mechanical pulping in total electricity demand for pulp and paper making per EU Member State.*

																%
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU	
5%	42%	31%	0%	12%	50%	24%	31%	34%	0%	23%	0%	21%	0%	46%	35%	

<sup>44</sup> According to CEPI this energy saving is far too high; savings of about 5% have been achieved in test runs, according to CEPI.

Since the process is still in the demonstration phase and it is not clear at the moment whether all TMP pulp can be replaced by PGW-S pulp, we assume a maximum implementation of 10% in 2010.

*Heat recovery in thermo-mechanical pulping* – The heat produced in the process of thermo-mechanical pulping can be recovered as low pressure steam in an evaporator reboiler system [Martin *et al.*, 2000]. The steam generated can be used in the pulping process itself or in paper making in case of an integrated mill. Heat recovery systems can be expected to save between 3.2 to 5.5 GJ/tonne of pulp [Martin *et al.*, 2000]. We will calculate with an average value of 4.4 GJ/tonne. Electricity demand will increase by 0.5 GJ/tonne. Installation costs vary widely. An average value is € 21/tonne of pulp (€ 4.4 GJ saved annually). Operation and maintenance costs will increase by € 18/tonne of pulp (€ 4.1/GJ saved annually). This measure is already common, we assume an average penetration of 50% in 1990 and maximum penetration of 80% in 2010<sup>45</sup>.

*Refiner improvements in mechanical pulping* - The electricity demand for refining can be reduced by several options: refiner control strategies, conical instead of disk refiners and decreasing the consistency of pulping to 30% from 50% [Martin *et al.*, 2000]. Martin *et al* [2000] estimate total savings for the US industry at 11% of the electricity demand for pulping. If we make the same assumption for the EU the saving would be about 0.35 GJ/tonne of pulp. Investment costs are € 23/GJ saved annually and O&M-costs increase by € 7.4GJ saved annually. In the EU the penetration of this measure is already high (estimate 75%)<sup>46</sup>.

*Pressing to higher consistency, e.g. by extended nip press (paper making)* – Removal of water in the pressing section is far less energy-intensive than in the drying section. Therefore, an increase in the fibre concentration after the pressing section can result in a reduction of the energy demand of the drying section. This can be achieved by using an extended nip press (or long nip press). With an extended nip press the fibre concentration after the pressing section can be increased to 53-55% compared to 42-48% for conventional pressing. On average an increase of 4% seems possible [De Beer *et al*, 1994]. Each percent increase results in a 4% saving on the steam demand of the pressing section [Lewyta, 1983]. Since 90% of the heat demand of a paper mill is for the drying section, a maximum saving of 0.8 GJ/tonne results. Because this measure cannot be applied equally to all paper grades we use a saving of 0.5 GJ/tonne. The electricity demand will increase by about 0.05 GJ/tonne of paper due to increased used of vacuum and driving power. Investment costs are € 25/GJ saved annually [De Beer *et al*, 1994]. A maximum penetration of 95% is assumed since this measure competes with the next measure: improved pressing techniques.

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<sup>45</sup> Data for the percentage of heat recovery per country are not available. CEPI reports that in Finland this is already 100%.

<sup>46</sup> According to CEPI this potential has been exhausted in the EU.

*Improved pressing techniques, e.g. impulse drying or condensing belt drying* – The production speed of paper machines is limited by the drying rate of the conventional drying section. A combination of pressing and drying can increase the drying rate and simultaneously reduce the energy consumption. Condensing belt drying is developed by Valmet-Tampella in Finland. The first commercial units are already in operation, albeit at a small scale. It results in improved sheet properties and easy operation at high speeds. Energy can be saved because heat can be recovered easier than with conventional drying [Valmet, 1998]. Saving on the heat demand is estimated to be on the order of 0.5-1.0 GJ/tonne paper. Impulse drying involves pressing the paper between one very hot rotating roll (150-500°C) and a static concave-shaped press with a very short contact time. Sheet dryness can be increased to 55-78%, depending on the type of paper [Wahlstrom, 1991]. Impulse drying is still not commercial, despite international R&D efforts [Luiten and Blok, 1998]. It is also not clear whether impulse drying will result in an energy saving. Therefore, this technology is not expected to be implemented before 2010.

A first commercial condensing belt unit with a capacity of about 25 kt a year had investment costs of € 11.1 million (1990) (€ 12.5 million (1996)) [Lehtinen, 1996]. Contributing all investment costs to energy savings would result in investment costs of € 450-900/GJ saved annually. However, condensing belt drying is mainly developed for its other benefits, like improved paper quality and easier operation. Furthermore, economies of scale might reduce the investments. Finally, compared to conventional paper drying condensing belt drying is less complex, more compact and probably less expensive. We assume that at 5% of paper making capacity a choice has to be made between improving the current drying section or installing a new technology, like impulse drying. For this 5% we assume small investment costs: € 5/GJ saved annually. Condensing belt drying might also be used at the other paper making capacity. However, since this involves high investments, we do not consider this option.

*Reduced air requirements, e.g. by humidity control in paper machine drying hoods* – In most paper mills the drying section is covered with a closed hood. By better insulation of the hood condensation of water vapour shall occur at a higher temperature reducing the amount of ventilation air required. An average dew point increase of 4°C was possible in The Netherlands in 1990, resulting in a reduction of the heat demand of 0.3 GJ/tonne of paper. Investment costs are estimated at € 35/GJ saved annually and operation and maintenance costs at € 1/GJ saved annually [De Beer *et al*, 1994].<sup>47</sup>

*Miscellaneous measures* – Table 2.28 gives an overview of miscellaneous measures that can be taken in paper and pulp mills.

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<sup>47</sup> CEPI does not agree with generalising the one example for the Netherlands to all EU countries.

Table 2.28. Miscellaneous measures that can be taken paper mills and pulp mills

Low cost tranche (< 25/GJ saved annually)	High cost tranche (> 25/GJ saved annually)
<b>Paper mills</b>	
Better dimensioning refiners More efficient steam distribution Energy management Optimisation of process control Use less steam in stock preparation <b>Savings:</b> 0.5 GJ of heat 0.2 GJ of electricity	Energy efficient motor drives Direct drive motors Waste heat recovery Matching components pumping system <b>Savings:</b> 0.2 GJ of heat 0.3 GJ of electricity
<b>Pulp mills</b>	
Energy management Optimisation of process control <b>Savings:</b> 0% on fossil fuel demand 10% on electricity demand	Energy efficient motor drives Incineration of residues (bark, black liquor) for power generation <b>Savings:</b> 0% on fossil fuel demand 10% on electricity demand

*New capacity pulp and paper* - According to the baseline scenario in Primes shares of the new pulp and paper capacity (capacity installed in the period between 1990 and 2010) for the Member states are depicted in Table 2.29. In the analysis it is assumed that the growth is equally distributed over pulp and paper.

Table 2.29. Share of new pulp and paper production capacity in 2010, according to the baseline scenario in Primes [1999]

															units	
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU	
19%	20%	0%	0%	12%	33%	0%	14%	0%	8%	0%	20%	0%	19%	0%	-	

The best practice SEC for paper making (averaged for different types of paper) in 1995 was 4.5 GJ of fuel/tonne paper and 1.8 GJ of electricity/tonne paper<sup>48</sup> [Phylipsen, 2000].

## 2.8 FOOD, BEVERAGES AND TOBACCO INDUSTRIES

This sector includes all activities of processing agricultural products, fish, meat and tobacco. The total demand for energy in the EU was about 890 PJ in 1990, or 8% of the EU industrial energy consumption. See Table 2.30 for a division over EU Member States.

<sup>48</sup> CEPI considers the value for fuel too low and for electricity as accurate.

Table 2.30. 1990 final energy demand in the food, beverages and tobacco industries in EU Member States, divided into fuel and electricity [Primes, 1999].

	Total final	Fuels	Electricity
	<b>PJ</b>		
Austria	13.3	8.9	4.4
Belgium	28.0	14.9	13.1
Germany	231.4	171.1	60.3
Danmark	25.8	19.3	6.5
Spain	64.8	46.4	18.4
Finland	15.4	9.4	6.0
France	152.3	99.2	53.1
UK	144.0	105.7	38.3
Greece	13.0	10.0	3.1
Ireland	13.9	9.3	4.6
Italy	81.7	56.9	24.8
Netherlands	66.6	48.1	18.5
Portugal	12.8	8.6	4.2
Sweden	23.2	16.8	6.4
<b>EU</b>	<b>886.3</b>	<b>623.5</b>	<b>262.8</b>

The most energy-intensive industries in this sector are dairy products and sugar production. We will deal with these sectors separately. For all other sectors a set of generic measures will be proposed, covering the major energy functions: cooling, space heating and drive power.

## 2.8.1 Dairy products

### 2.8.1.1 Key parameters

There is a large variety in dairy products, but the raw material is in all cases milk. In 1988 the intake dairies of 10 EU member countries (excl. Luxembourg) was about 100 million tonne of milk [EC, 1993]. There are large differences in the average intake of the dairies. In the Netherlands this was 334,000 tonne of milk per dairy whereas in Italy this was only 3,000 tonne of milk per dairy [EC, 1993]. Although no data are available to underline this, it is most probable that the energy-efficiency of the larger dairies is better than that of the smaller dairies.

The products that require most energy for production are milk powder and whey powder and concentrated products. Powders are produced in two stages. First the milk is concentrated to about 50% dry matter. Subsequently, the dry matter content is increased to over 97% in the drying process. The energy consumption of the dryers is about ten times of that of the evaporators per tonne of water evaporated. In 1990 the average steam demand for evaporation in the Netherlands was 0.15 kg per kg of water evaporated [Oltshoorn, 1993]. Since the Dutch dairy industry is already efficient, we assume that the European av-

erage steam demand is twice as high. Two stage evaporators, the conventional technology has a steam demand of 0.3-0.5 kg/kg. Drying in drying towers requires about 5 MJ of steam per kg of water evaporated and 0.5 MJ of electricity per kg water [Karskens, 1989]. Using these average values for all Member States we can estimate the share of evaporation and drying in the fuel demand of the food sector, see Table 2.31. The share in the electricity demand is negligible.

Table 2.31. Share of concentration and drying of dairy products in the total fuel consumption of the sector Food, beverages and tobacco per EU Member State. Based on the production of milk powder (1990) [Eurostat, 1996].

AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
10%	21%	9%	16%	3%	12%	20%	5%	0%	55%	0%	0	14%	6%	1%	10%

<sup>1</sup> FRG only

### 2.8.1.2 Options to improve the energy efficiency

*Application of efficient evaporation processes* – Traditionally, evaporation was performed in a two-stage evaporator, with a steam demand of 0.3-0.5 kg/kg water evaporated. With a six-stage evaporator with a thermocompressor on the third stage, savings on the steam demand on the order of 0.2-0.4 kg per kg of water evaporated can be achieved. The electricity demand increases by 6 MJ per tonne of water evaporated [Mil and Straatsma, 1989]. An even larger reduction on the steam demand can be achieved by applying mechanical vapour recompression (MVR). MVR should be combined with a two-stage evaporator to achieve the same dry-matter content as with a six-stage evaporator. The steam demand can be brought down to 0.03 kg/kg water evaporated, whereas the electricity demand increases to 50 MJ of water evaporated. Reverse osmosis can also be used to concentrate milk. A combination with a two-stage evaporator is also required and the energy demand is comparable to an MVR with two-stage compressor.

Retrofitting of existing evaporators to MVR or RO is technically difficult [Van der Wekken and Quaak, 1990]. Consequently, full replacement costs have to be used, being € 55/GJ saved annually.

## 2.8.2 Sugar industries

### 2.8.2.1 Key parameters

The EU is world's largest producer of sugar. In the EU sugar is mainly produced from beet. The production processes consists of the following phases:

1. extraction of beet plant's sucrose content by treating beet slices with steam and immersing them into tanks of hot water to produce a raw juice;

2. purification, evaporation and crystallisation of the juice;
3. processing of crystals to obtain sugar in its marketable form.

Sugar is normally produced in a three-month period after the harvest of the beets (in the Netherlands from September to December). During the campaign the steam demand is about 9-11 GJ/tonne sugar and the electricity demand 0.8-1.0 GJ/tonne sugar [De Beer *et al*, 1994]. Energy intensive steps are evaporation, extraction and beet pulp drying. At modern plants CHP units are installed. Between the campaigns the energy demand is very small.

Outside Europe sugar extraction out of sugar cane is a common process. The energy to drive is process is generally obtained from bagasse, a side-product of the process. Since the bagasse production is more than sufficient to meet the energy demand, energy efficiency has not been an issue in these plants the past decades [Van Groen, 1999]. Therefore, it is of little use to compare the energy efficiency of sugar from beet with that of sugar from cane.

Table 2.32 gives an overview of the sugar production in the EU Member States. The total EU production was 15% of the world production [EC, 1993].

Table 2.32. *White sugar production in EU Member States during the 1990/1991 campaign [CEFS, 2000].*

																1000 tonnes	
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU		
415	1030	4301	544	967	169	4357	1237	287	226	1458	-	1232	2	405	16630		

Based on an average specific fuel demand of 10 GJ/tonne and a specific electricity demand of 0.9 GJ/tonne, the share of the sugar industry in the energy demand of the food sector can be estimated. The results are given in Table 2.33 and Table 2.34. For countries where no data is available the EU average shares have been used.

Table 2.33. *Share of the sugar industry in the total fuel demand of the food sector.*

																%	
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU		
39%	58%	21%	24%	18%	15%	37%	10%	24%	20%	22%	-	22%	0%	20%	20%		

Table 2.34. *Share of the sugar industry in the total electricity demand of the food sector.*

																%	
AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU		
9%	8%	7%	8%	5%	3%	8%	3%	9%	5%	6%	-	7%	0%	6%	6%		

### 2.8.2.2 Options to improve the energy efficiency

Several options are available to improve the energy efficiency of the two energy intensive operations: evaporation and beet pulp drying. It is also possible to improve the process as a whole using tools such as pinch analysis.

*Evaporation* – In the evaporation stage the liquid resulting from the purification process is concentrated from about 16% to 65% solids content. This is done in a series of usually four or five, evaporation vessels where the water is boiled off. These vessels are highly integrated. Vapours of one vessel are used to boil off water in the next.

The energy consumption of evaporation can be reduced by increasing the number of stages. At a plant of British Sugar the number of stages was extended from 5 to 6, resulting not only in an energy saving of about 0.7 GJ per tonne of sugar but also in a capacity increase of 20% [CADDET, 2000]. Investment cost were € 2/GJ saved annually for only the new heat exchanger and € 3.3/GJ saved annually when also a new steam boiler is required [CADDET, 2000].

*Beet pulp drying* – Beet pulp is usually dried by hot air and sold as animal feed. The energy demand is about 3 GJ/tonne sugar [Austmeyer and Röver, 1988]. Several options are available to decrease this energy demand: high performance pressing, drying in a fluidised bed, mechanical vapour recompression and diffusive dewatering [De Beer *et al*, 1994]. Installing mechanical vapour recompression requires a retrofit of the steam system and the evaporation stages. Furthermore, the electricity demand increases. It has been applied in several sugar plants in Europe [Austmeyer and Röver, 1988].

*Process integration* – A sugar plant is a highly integrated process. Changing one unit operation has consequences for another. Optimising the process as a whole is possible using a tool as pinch analysis. For a sugar plant in the Netherlands a saving on the fuel demand of 6% by optimisation of the heat exchanger was found to be attainable [De Beer *et al*, 1994]. Investment costs are € 70/GJ saved annually.

An overall potential saving on fuel demand of 4 GJ/tonne is seen as attainable [Austmeyer and Röver, 1989]. Investment costs vary strongly between measures and plants. We assume average investment costs of € 40/GJ saved annually. The electricity demand will increase on the one hand by the use of mechanical vapour recompression. On the other hand, a decrease is possible by several options, e.g. installation of efficient fans, pumps and motors. Overall we assume that a small saving is possible. This is dealt with at measures for other food and beverages.

### 2.8.3 Other food, beverages and tobacco industries

For the other industries in the sector food, beverages and tobacco we assume two sets of measures.

*Overall - Low cost tranche* - In this set all measures are included that have investment costs of less than € 25/GJ saved annually. Examples are: good house-keeping, adjustable speed drives, reduce leakage in pressurised air systems, efficient lighting and process optimisation. Average saving on fuel demand of these measures is estimated to be 10% and on electricity demand 15%. Average investment costs are € 20/GJ saved annually.

*Overall – High cost tranche* - In this set all measures are included that have investment costs of more than € 25/GJ saved annually. Examples are: heat recovery, improvement of cooling installations, efficient motors and appliances, more efficient drying of starch, heat pumps and membrane separation. Average saving on fuel demand of these measures is estimated to be 15% and on electricity demand 20%. Average investment costs are € 50/GJ saved annually.

## 2.9 OTHER INDUSTRIES

Other industries include textile industry, wood manufacturing industry, printing and publishing, building and constructing activities and a number of miscellaneous industries. Because of the large number of different processes and the relatively small share in the energy demand these sectors will not be investigated in detail.

### 2.9.1 Options to improve the energy efficiency

Although there are many measures that are specific to one industrial sector, reduction of the energy demand in the other industry can also be achieved by generic measures. Table 2.35 gives some examples of generic measures that can be taken in the other industry to reduce the energy demand.

Table 2.35. *Examples of energy efficient measures that can be taken in the other industry.*

Low cost tranche ( 10/GJ saved annually)	High cost tranche ( 30/GJ saved annually)
Fuel (15% saving in the period 1990-2010 ) <ul style="list-style-type: none"> <li>- good housekeeping measures</li> <li>- energy management</li> <li>- insulation (roof, cavity wall, reduction ventilation rate, ventilation heat recovery)</li> <li>- more efficient driers in textile and wood industry</li> </ul>	Fuel (15% saving in the period 1990-2010 ) <ul style="list-style-type: none"> <li>- process heat, more efficient burners</li> <li>- heat recovery</li> <li>- insulation (floor, heavy wall, double glazing)</li> <li>- indoor climate optimizer</li> <li>- condensing boilers</li> <li>- heat pumps</li> </ul>
Electricity (15% saving in the period 1990-2010 ): <ul style="list-style-type: none"> <li>- good housekeeping measures</li> <li>- reduce leakage in pressurised air systems</li> <li>- more efficient lighting systems</li> <li>- more efficient machines</li> </ul>	Electricity (15% saving in the period 1990-2010 ) <ul style="list-style-type: none"> <li>- adjustable speed drives</li> <li>- energy efficient motors</li> <li>- matching pumps and fans to load</li> <li>- reduce friction in piping and ducting</li> </ul>

## 2.10 DISCUSSION AND CONCLUSIONS

The total reduction potential identified is 395 Mt CO<sub>2</sub>, compared to the frozen technology reference level. An overview of the individual industrial carbon dioxide emission reduction options on costs and reduction potential is given in the Table 4.1 (page 68).

Table 2.36 and Table 2.38 give an overview of the technical potentials for reducing energy-related CO<sub>2</sub> emissions by industrial subsector and by EU Member State. Note that these potentials represent the technical potential, i.e. representing the emission in 2010 that can be avoided by implementation of all (in this report identified) technically achievable energy-efficiency improvements. The economic feasibility is not taken into account into these tables. Table 2.37 gives the CO<sub>2</sub> emission reduction potential for four cost brackets.

Table 2.36 shows the emission reduction potentials by industrial subsector for the EU as a whole. For each subsector 1990 and 2010 emissions include fuel emissions and emissions related to electricity and steam consumption in that subsector. The emission reduction potential reflects the effect of efficiency improvement measures on both fuel and electricity-related emissions. The implementation of CHP is not included in the subsectoral potentials. The table also shows the additional effect of implementing CHP on the emission reductions achievable for the industry as a whole. The bottom line of Table 2.36 shows the effect of the increased efficiency (and fuel switch) of the fossil-fuel based power generation on the avoided emissions in industry (note that the emission reduction potential of renewable energy implemented in the electricity sector is not included in Table 2.36. It has been included in the potentials in Table 2.38).

Table 2.38 shows the emission reduction by Member State for the EU as a whole, including the effects of options taken in the energy supply sector on emissions related to industrial electricity and steam consumption.

Table 2.36. *Technical potentials for reducing energy-related CO<sub>2</sub> emissions in industry as described in this report. Potentials are for the EU as a whole. The emissions in 2010 are based on the frozen technology reference case<sup>1</sup>. The subsectoral emission reductions include the effects of fuel savings as well as electricity savings. Emission reduction from industrial CHP are only given for the industry as a whole. In addition, the effect is given in case the efficiency improvement in the electricity generating sector is included.*

Subsector	Direct and indirect emission		Emission Reduction (4)	Direct and indirect emissions after reductions		
	Mt CO <sub>2</sub>		Mt CO <sub>2</sub>	Mt CO <sub>2</sub>	% compared to 1990	compared to 2010
	1990	2010 frozen technology reference level	2010	2010		
Iron & steel	246	266	48	218	89%	82%
Non-ferrous metals	50	68	11	57	115%	84%
Chemicals	254	420	85	335	132%	80%
Non-metallic minerals	232	276	34	242	104%	88%
Pulp & paper	135	218	56	162	120%	74%
Food, beverages & tobacco	107	166	53	113	106%	68%
Other	264	374	108	266	101%	71%
<b>Total</b>	<b>1287</b>	<b>1789</b>	<b>395</b>	<b>1394</b>	<b>108%</b>	<b>78%</b>
Including CHP <sup>2</sup>			729	1060	82%	59%
Including Power Supply <sup>3</sup>			884	905	70%	51%

Notes: <sup>1</sup> This means a change in emissions is only caused by a change in activity (production). Energy efficiency, sector structure and fuel mix are all assumed constant to avoid double-counting of emission reduction options; <sup>2</sup> efficiency improvement and lower carbon intensity as a result of replacement by and new additions of gas-fired CHP plants. Shifts to renewable energy within the electricity sector have not been included. <sup>3</sup> As in <sup>2</sup>, but including renewable energy, <sup>4</sup> compared to the frozen technology reference level.

Table 2.37. *Emission reduction potential for CO<sub>2</sub> in industry in 2010 compared to the frozen technology reference level. The reduction potentials are given for four cost brackets. Costs are expressed in euro/tCO<sub>2</sub> avoided.*

Emission reduction (Mt CO <sub>2</sub> )	< 0 euro	0 - 20 euro	20 - 50 euro	> 50 euro	Total
Chemicals	78	7	0	0	<b>85</b>
Food, beverage & tobacco	53	0	0	0	<b>53</b>
Iron and steel	3	29	13	2	<b>49</b>
Non-ferrous metals	10	0	0	1	<b>11</b>
Non-metallic minerals	33	1	0	0	<b>34</b>
Other	108	0	0	0	<b>108</b>
Paper & pulp	49	1	7	0	<b>56</b>
<b>Total</b>	<b>334</b>	<b>38</b>	<b>20</b>	<b>3</b>	<b>395</b>

Table 2.38. Technical potentials for reducing energy-related CO<sub>2</sub> emissions in industry in individual Member States. The total emissions in 2010 are based on the frozen technology reference case. The emission reductions include the effects of fuel savings as well as electricity savings and industrial CHP. Also included is the effect of measures taken in the electricity generating sector on the emission related to industrial electricity consumption (including efficiency improvement, fuel switch and renewables).

Country	Direct and indirect emissions		Emission Reduction (1)	Direct and indirect emissions after reductions		
	Mt CO <sub>2</sub>		Mt CO <sub>2</sub>	Mt CO <sub>2</sub>	% compared to 1990	% compared to 2010
	1990	2010 frozen technology reference level	2010	2010		
AUT	33	45	15	30	91%	67%
BEL	52	70	26	44	86%	63%
DEU	402	510	226	284	71%	56%
DNK	20	24	17	7	35%	29%
ESP	96	146	84	62	64%	42%
FIN	22	42	22	20	89%	47%
FRA	125	196	98	98	79%	50%
GBR	219	326	162	164	75%	50%
GRC	37	49	24	25	68%	51%
IRL	12	21	12	9	74%	42%
ITA	174	214	112	102	58%	48%
NLD	57	81	47	34	61%	42%
PRT	20	33	19	14	72%	43%
SWE	19	31	20	11	57%	35%
EU	1287	1789	884	905	70%	51%

<sup>1</sup> compared to the frozen technology reference level.



### 3. OPTIONS TO REDUCE N<sub>2</sub>O EMISSIONS FROM INDUSTRIAL PROCESSES

#### 3.1 INTRODUCTION

The two major industrial processes that lead to emissions of nitrous oxide are the production of adipic and nitric acid and together these accounted for 28 % of total emissions nitrous oxide emissions in 1990 [UNFCCC, 1999]. Based on data from CORINAIR90 and other sources, adipic acid was responsible for almost two-thirds (61 %) of industrial process emissions, and nitric acid for almost all of the remainder (38 %).

*Adipic acid* is a raw material used mainly in the manufacture of 6,6 nylon, which is used in industrial carpets; some adipic acid is also used in the manufacture of engineering plastics and low temperature lubricants. *Nitric acid* is a raw material mainly used as a feedstock in fertiliser production, but also in the production of adipic acid and explosives. Within the EU about 80% of nitric acid production is used for fertiliser production.

Some other chemical processes have also been identified as potentially leading to N<sub>2</sub>O emissions. These are generally processes involving a nitrogen compound, or a catalytic reduction step. Within the EU other industrial processes reported as leading to emissions in CORINAIR90 included:

- petroleum products processing;
- acrylonitrile production;
- ethylene production;
- fluid catalytic cracking;
- furnace steel plant;
- aluminium production;
- paper and pulp processes.

However, emissions from these processes were estimated to be only 1% of the total 1990 industrial process emissions.

#### 3.2 EMISSIONS

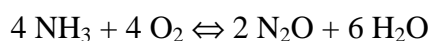
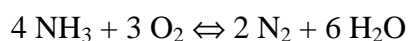
##### 3.2.1 Emission mechanisms

The starting point for the manufacture of Adipic acid is cyclohexane, which is used to produce 'KA' (a mixture of cyclohexanol and cyclohexanone), which is then oxidised with nitric acid to produce adipic acid. N<sub>2</sub>O is a side product of this final oxidation step (Olivier, 1993). Emissions are estimated at 300g N<sub>2</sub>O per kilogram of Adipic acid produced (Thiemens and Trogler, 1991).

Most commercial manufacture of nitric acid is based on the oxidation of ammonia during which N<sub>2</sub>O is produced as a by-product. There are three main steps in the production process:

- i. catalytic oxidation of ammonia (NH<sub>3</sub>) (in the presence of air) to nitrogen monoxide (NO);
- ii. oxidation of nitrogen monoxide to the dioxide (NO<sub>2</sub>);
- iii. absorption of NO<sub>2</sub> in water to produce medium concentration nitric acid (HNO<sub>3</sub>).

It is the first of these stages which leads to emissions of N<sub>2</sub>O. Using suitable catalysts, about 93-98% of the ammonia is converted to NO, but the rest of the ammonia is converted into nitrogen (mostly) and nitrous oxide in the following undesired side reactions:



The N<sub>2</sub>O and N<sub>2</sub> pass through the other stages of the process and are released in the flue gas along with any unreacted NO and NO<sub>2</sub>.

The exact mechanism by which the N<sub>2</sub>O is produced is still not well understood, and emissions of N<sub>2</sub>O per tonne of nitric acid production can vary by a factor of three between plants, with high pressure systems generally having a higher emission factor. Measurements by Du Pont have shown emission factors of 2 - 9 g N<sub>2</sub>O per kg of nitric acid produced, but it is not known how representative are these factors. Measurements by other manufacturers have shown emissions of 7 ± 2 g per kg.

### 3.2.2 Emissions in EU-15

In the EU, adipic acid is produced in 4 countries, Germany, France, Italy and the United Kingdom. Nitric acid is produced widely in the EU, with 13 countries having emissions from this process in 1990 (Austria, Belgium, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden and the United Kingdom). The breakdown of emissions for the EU in 1990, derived from UNFCCC and CORINAIR90 data, and the totals for 1995 are shown in Table 3.1.

Table 3.1 Emissions of N<sub>2</sub>O from industrial processes in 1990 and 1995

	1990				1995 <sup>1</sup>
	Adipic acid (kt)	Nitric acid (kt)	Other proc- esses (kt)	Total (kt)	Total (kt)
Austria	0.0	0.6	0.0	0.6	0.5
Belgium	0.0	10.1	1.4	11.5	13.8
Denmark	0.0	0.0	0.0	0.0	0.0
Finland	0.0	3.0	0.0	3.0	2.6
France	53.2	36.7	0.1	90.0	80.4
Germany	67.8	15.2	0.0	83.0	82.0
Greece	0.0	2.0	0.3	2.3	1.8
Ireland	0.0	2.6	0.0	2.6	2.6
Italy	14.8	8.7	0.0	23.5	20.4
Luxembourg	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	29.9	1.6	31.5	31.6
Portugal	0.0	1.9	0.0	1.9	1.9
Spain	0.0	10.4	0.0	10.4	8.4
Sweden	0.0	2.5	0.1	2.6	2.3
United Kingdom	81.1	14.1	0.0	95.2	66.1
EU 15	216.9	137.8	3.4	358.2	314.4

<sup>1</sup> Note no split is available for 1995 and there is no 1995 data for Portugal, so 1994 values entered instead

### 3.3 EMISSION REDUCTION OPTIONS

#### 3.3.1 Introduction to the measures

Potential options for reducing emissions from both adipic acid and nitric acid manufacture fall into four main categories:

- optimisation of the production process;
- alternative production processes;
- use of 'end-of-pipe' technology to reduce emissions;
- reduced demand.

### 3.3.2 Options for reducing emissions from adipic acid production

#### 3.3.2.1 Description

##### *Optimising the adipic acid production process*

One option is to re-use the  $N_2O$  from adipic acid production to manufacture nitric acid. The technology produces nitric acid by burning  $N_2O$  at high temperatures in the presence of steam. This approach has the twin advantages of utilising the  $N_2O$  produced by adipic acid manufacture, while avoiding the  $N_2O$  generated from conventional nitric acid production (Scott 1998).

An alternative approach is to re-use the  $N_2O$  rich off-gas to selectively oxidise benzene to phenol. The US company Solutia has recently announced that it will build such a system by 2002, replacing the thermal off-gas treatment currently used at their Pensacola plant (Reimer 1999). The company suggests that the new plant should result in savings equal to 20% of the cost of making the adipic acid.

##### *End-of-pipe technologies*

The two most widely used end-of-pipe technologies are catalytic decomposition and thermal destruction.

In *catalytic decomposition*, a catalyst bed (of metal oxides such as CaP and MgO) is used to decompose the  $N_2O$  into  $N_2$  and  $O_2$ . The reaction is strongly exothermic and the heat produced must thus be removed; if there is a suitable demand on the production site, then it may be recovered and used to produce steam. Potential problems with the process include the need to recharge poisoned catalyst twice a year, and the complex design needed to generate useful steam from the process. A simpler, once-through version of this process is being piloted at a site in the USA.

An alternative process is *thermal destruction* in which involves combustion of the off-gases in the presence of methane. The  $N_2O$  acts as an oxygen source and is reduced to nitrogen, giving non-negligible quantities of NO and some residual  $N_2O$ . The combustion process can be used to raise steam, if a demand exists on site.

#### 3.3.2.2 Current practice

All the major manufacturers in Europe, with the exception of Radici Chimica in Italy, have installed abatement plant as summarised in Table 3.2.

Table 3.2 Implementation of abatement options at adipic acid plant

Country	Manufacturer	Technique	Efficiency by 2000	Implementation date
United Kingdom	Du Pont	Thermal	94 %	1998
France	Rhodia	Conversion to HNO <sub>3</sub>	98 %	1998
Germany	Bayer	Thermal	96 %	1994
Germany	BASF	Catalytic	95 %	1997

In the United Kingdom, the high cost of purchased steam at the Dupont site at Wilton makes thermal N<sub>2</sub>O abatement an attractive option. The heat of N<sub>2</sub>O decomposition, combined with fuel energy, helps provide low-cost steam. A slightly different reducing furnace technology was developed by Bayer and started operation in 1994. The other German manufacturer, BASF, installed a catalytic system at their Ludwigshafen plant in 1997. In June 1998, the French company Alsachimie, a subsidiary of Rhodia, brought on stream a system to convert N<sub>2</sub>O to nitric acid at their Chalampe site.

Production in Italy is at a lower level than in other European countries and at the present there appears to be no plans to abate emissions.

### 3.3.2.3 Alternatives

In the past, several manufacturers used air oxidation (rather than nitric acid oxidation) of KA to produce adipic acid. However this process produced low quality adipic acid and is not a commercial option. Research has been carried out by some manufacturers into a butadiene carbonylation process (which does not produce N<sub>2</sub>O emissions). This was abandoned on the basis that it was too costly (ENDS, 1996) and one manufacturer has commented that they do not expect this route to be exploited commercially “in the next 25 years if ever”. No costs have been presented for this option.

In the longer term, a possible option is to use petroselenic acid as a substitute for adipic acid. Petroselenic acid can be obtained from coriander, so that the commercial cultivation of coriander could provide a source. Alternatively, there is ongoing research into using biotechnology to genetically modify oil-seed rape to produce petroselenic acid. More work would be needed to quantify the costs and potential of this option.

### 3.3.2.4 Implementation

In 1990, none of the adipic acid plants in the EU had any nitrous oxide abatement equipment. As discussed in earlier, all plants except the one in Italy have now been fitted with abatement of some kind.

The realistic maximum level of abatement in 2010 would be for all plants (including the Italian plant and any new facilities) to have N<sub>2</sub>O abatement fitted. The precise abatement technique used would depend of plant specific criteria, such as the need and cost of steam and space limitations.

### 3.3.2.5 Costs

Very little cost data is available on abatement options due to commercial sensitivity. However, the costs of the two end-of-pipe technologies, catalytic decomposition and thermal destruction, are likely to be broadly similar with the choice for a particular plant being dependent upon factors noted under Implementation. Re-using the N<sub>2</sub>O from adipic acid production to manufacture nitric acid can also be a cost-effective option in some circumstances.

An indicative calculation of the cost of abatement has therefore been made as shown in Table 3.3, based on the reported capital costs for a German plant (AEA Technology 1988) and the following assumptions:

- The non-recurring capital cost is 12.8 million €<sub>1990</sub> (27 million DM in 1995 prices).
- Annual recurring costs are assumed to be 10% the investment cost.
- The option has a lifetime of 15 years.
- The plant treats 58,000 tonnes of N<sub>2</sub>O per year, and is effective in removing 95 per cent of emissions (Reimer 1999).
- The cost effectiveness of the option is calculated using a discount rate of 4%

Table 3.3 Summary of the cost of N<sub>2</sub>O abatement from adipic acid plants

Capital cost (million €)	12.8		
Annual costs (million €)	1.3		
Emissions abated per year (tonnes)	55,100		
<b>Cost effectiveness at discount rate of</b>	<b>4%</b>	<b>2%</b>	<b>6%</b>
Cost-effectiveness (€/t N <sub>2</sub> O abated)	44	42	48
Cost-effectiveness (€/t CO <sub>2</sub> eq abated)	0.1	0.1	0.2

### 3.3.2.6 Country specific implications

Since adipic acid plant in France, Germany and the United Kingdom already have N<sub>2</sub>O abatement installed, the cost of any additional abatement would fall on Italy.

### 3.3.3 Options for reducing emissions from nitric acid production

#### 3.3.3.1 Description

##### Optimising the production process

The production process may be optimised so that the yield of NO is maximised (and hence the emissions of N<sub>2</sub>O minimised) in the first oxidation step. It is difficult to estimate the reduction in emissions that might result from improving the production process, although the range in emission factors for different sites indicates that some improvement should be possible. One study (de Jager et al, 1996) has estimated that in the short term a 10% reduction in emissions might be achievable with no significant additional costs, although these assumptions have not been validated. Most modern plants are already well optimised and operate at an efficiency of 94-96.

##### Thermal Decomposition

For new plant, it is possible to redesign the ammonia oxidation units so that N<sub>2</sub>O is thermally decomposed in the chamber below the process catalyst, giving a reduction in N<sub>2</sub>O emissions of 70 to 85% and an overall emission in a modern plant of 2 g N<sub>2</sub>O per kg nitric acid. The technology which was developed by Hydro Agri was successfully installed in a new plant (2000 million tonne per day plant) in Norway in 1990; capital costs of the plant were increased by about 5-6%, but there is no increase in operational costs.

The technology is not suitable for retrofitting, due to the need for significant redesign of the ammonia oxidation units. It is highly unlikely that any new nitric acid plant will be built in the EU before 2010, so this option will not be implemented before 2010. In the longer term however, it could ensure that all new plant have low levels of N<sub>2</sub>O emissions.

##### Selective Catalytic Reduction

Two selective catalytic reduction (SCR) systems are currently under development, one in which the catalyst abates N<sub>2</sub>O in the process gases, and one which works in the tail gases.

When SCR is used in the process gases, the catalytic reduction occurs at a temperature of 800-900 C just below the noble metal gauzes used to perform the catalytic oxidation of ammonia to NO<sub>x</sub>. This is well above the light-off temperature of the gauze. The catalyst is introduced as a loose bed under the gauze.

zes, and for certain furnace designs is relatively simple to retrofit. Trials of this technology have been running since March and July 1999 in Germany and the Netherlands, and have reduced emissions by 70 to 80% (Kuhn et al, 1999). The thermal stability of the catalyst has yet to be proven, and current testing is intended to check how long the catalyst works satisfactorily without decreasing the NO yield. It is hoped that this technology might be commercially available within 5 to 6 years.

For SCR in the tail gases, the most promising catalysts are generally based on relative expensive materials such as zeolites. Early catalysts of this type suffered from the problem that in order to work properly they required considerable amounts of additional energy input to raise the temperature of the flue gases. However, developments by a number of organisations are leading to catalysts that work at lower temperatures. For instance, ECN in the Netherlands has developed a Fe/Zeolite catalyst which achieved over 80% conversion of N<sub>2</sub>O to N<sub>2</sub> in a simulated flue gas mixture at a temperature of 350°C (Pels, 1999) and CRI Catalysts Ltd. report that they have developed a catalyst that is active at temperatures approximately 60-100 °C lower than those previously described in the literature (Clark 1999). The performance of these catalysts in real (rather than simulated) flue gases still needs to be demonstrated, as does their lifetime.

#### Use of Non-selective catalytic reduction (NSCR) for NO<sub>x</sub> abatement

Nitric acid plant also have to control emissions of nitrogen oxides (NO<sub>x</sub>) in tail gases. The use of *non-selective catalytic reduction (NSCR)* rather than selective catalytic reduction systems to reduce NO<sub>x</sub> other systems (such as SCR) has the added benefit of reducing N<sub>2</sub>O emissions to N<sub>2</sub>. Typical conversion efficiencies are about 90% for the NO<sub>x</sub> gases and 70% for the N<sub>2</sub>O, although under pilot plant trials, conversion efficiencies of 90% have been achieved for N<sub>2</sub>O (Environment Agency, 1999). NSCR on the other hand might increase the methane slip and increase energy use, both effects increasing the operational costs and the greenhouse gas emissions [Sund, 2000]. NSCR is most likely to be a mid to longer term option since at the moment SCR systems rather than NSCR systems are generally fitted to nitric acid plants. This is partly because SCR equipment usually has a lower capital cost than NSCR systems, but also partly for technical reasons. For example, the ammonia used in SCR is always available on a nitric acid plant, whereas the availability of hydrogen or the other reducing agent required for NSCR is site-specific (however the reducing agents used in NSCR are likely to be more inexpensive than ammonia). Conversion of NO<sub>x</sub> abatement systems from SCR to NSCR is considered unlikely.

#### Thermal dissociation of off-gases

The low concentration of nitrous oxide in the off-gas from nitric acid production means that thermal dissociation by the injection of fuel (natural gas, methane) is generally considered not to be a feasible option. However, in some cases off-gases could be mixed with high temperature off-gases from other nearby industrial processes, which would result in net nitrous oxide destruction. Reduction potential and costs would be site specific and have therefore not been quantified.

#### Reduced demand for nitric acid

The majority of nitric acid is used in fertiliser production. Reducing the use of inorganic fertilisers e.g. by increasing the efficiency with which fertilisers are used would thus lead to a reduction in N<sub>2</sub>O emissions. Increasing the use of organic fertilisers might also lead to lower N<sub>2</sub>O emissions, but more applied research is required to demonstrate this in a reliable manner. As the use of nitrogenous fertilisers is a major source of N<sub>2</sub>O emissions in the agricultural sector, these options are considered in the agricultural options.

#### **3.3.3.2 Current practice**

As noted above, the abatement technologies fitted to nitric acid plant are generally focused on reducing emissions of NO<sub>x</sub> and currently SCR is the favoured option due to its cost advantages. Consequently, there is little abatement of nitrous oxide emissions as a result of the use of NSCR and as far as is known, no implementation of selective catalytic reduction to abate nitrous oxide emissions, apart from the developments described above.

#### **3.3.3.3 Alternatives**

The biofiltration of off-gases using denitrifying bacteria is discussed by Oonk (1995). The applicability of this option to nitric acid production and the reduction potential and costs of the option are not yet known. It is likely that a residence time of several minutes at temperatures of 15 to 30 C would be required.

#### **3.3.3.4 Implementation**

To date there appears to have been no specific measures taken to abate N<sub>2</sub>O emissions from nitric acid production. It seems likely that one of the SCR technologies being developed will be ready for deployment by 2010 and would give a reduction of 70-80% in N<sub>2</sub>O emissions. The maximum realistic reduction by 2010 would be achieved by all plants using this technology.

### 3.3.3.5 Costs

#### Selective catalytic reduction in process gases

Only very preliminary costs are available for this technology (Schumacher, 2000). These are shown in and are based on:

- a plant producing 500 tonnes per day of nitric acid which operates at capacity for 90% of the year;
- unabated N<sub>2</sub>O emissions are 7 kg per tonne of nitric acid; the catalyst reduces emissions by 75%;
- the lifetime of the plant is 15 years
- the cost of the installation is not more than 114,000 €<sub>1990</sub> (250,000 DM<sub>2000</sub>) and the cost of a licence for the technology about 91,000 €<sub>1990</sub> (200,000 DM<sub>2000</sub>);
- the cost of the catalyst is 91,000 €<sub>1990</sub> (200,000 DM<sub>2000</sub>) and the catalyst is replaced every year.

Table 3.4 Costs of using SCR in process gases in nitric acid plants (€<sub>1990</sub>)

Capital cost (k €)	205		
Annual costs (k €)	91		
Emissions abated per year (tonnes)	862		
<b>Cost-effectiveness at discount rate of</b>	<b>4%</b>	<b>2%</b>	<b>6%</b>
Cost-effectiveness (€/t N <sub>2</sub> O abated)	127	124	130
Cost-effectiveness (€/t CO <sub>2</sub> eq abated)	0.4	0.4	0.4

#### Selective catalytic reduction in tailpipe gases

The costs of using selective catalytic reduction in tailpipe gases to abate emissions of N<sub>2</sub>O from nitric acid plant are shown in Table 3.5 (in 1990 EUR) and have been calculated using the following assumptions.

- The catalyst system costs 1.5 M €<sub>1990</sub> (\$2.25 M 1999 money) and can treat 80,000 m<sup>3</sup>/hr of flue gas;
- Emissions of N<sub>2</sub>O are assumed to be 7 g per kg of nitric acid production;
- The plant is assumed to operate at 90% availability over the year.
- Operating costs are between \$50 and \$100 per tonne of N<sub>2</sub>O abated (best estimate \$75).
- The efficiency of the catalyst is 80%. The overall lifetime of the plant is 15 years.

Table 3.5 Cost of using end of pipe SCR in nitric acid plants (€<sub>1990</sub>)

Capital cost (k €)	1500		
Annual costs (k €)	39 to 77		
Emissions abated per year (tonnes)	1136		
<b>Cost-effectiveness at discount rate of</b>	<b>4%</b>	<b>2%</b>	<b>6%</b>
Cost-effectiveness (€/t N <sub>2</sub> O abated)	153 to 187	137 to 171	170 to 204
Cost-effectiveness (€/t CO <sub>2</sub> eq abated)	0.5 to 0.6	0.4 to 0.6	0.5 to 0.7

### 3.3.3.6 Country specific implications

As reported above, most countries in the EU have nitric acid plant. Costs of abatement would therefore be widely spread across the EU with costs likely to be plant, rather than country, specific.

## 3.4 FROZEN TECHNOLOGY REFERENCE CASE

The frozen technology reference level for emissions of N<sub>2</sub>O from industrial processes (Table 3.6) have been calculated using the following assumptions:

- Production of adipic acid increases by an average of 2% per year over the period 1990 –2000 (the historical growth rate over the period 1988 – 1997) and then by 1.5 % per year up to 2010 (ChemExpo 1998). Production of nitric acid decreases by 13% over the period from 1990 to 2010.
- The activity of the remaining sources grows by 1 % per year over the period 1990 to 2010 (the average growth rate for the chemicals sector in the PRIMES modelling).
- No measures are introduced to reduce emissions over the period 1990 to 2010 (based on the projected decline in fertiliser consumption).

Table 3.7 shows the abatement case including the effects of reduction measures which are implemented over the period 1990 - 2000. This consists of the abatement of emissions from adipic acid plant as shown in Table 3.8.

Table 3.6. Emissions of N<sub>2</sub>O in 2010 with no abatement after 1990.

	Adipic acid (kt)	Nitric acid (kt)	Other processes (kt)	Total (kt)	Change from 1990 (%)
Austria	0.0	0.5	0.0	0.5	-13.0
Belgium	0.0	8.8	1.7	10.5	-8.8
Denmark	0.0	0.0	0.0	0.0	0.0
Finland	0.0	2.6	0.0	2.6	-13.0
France	58.8	31.9	0.1	90.8	0.9
Germany	74.9	13.2	0.0	88.1	6.2
Greece	0.0	1.8	0.3	2.1	-9.0
Ireland	0.0	2.3	0.0	2.3	-13.0
Italy	16.3	7.6	0.0	23.9	1.7
Luxembourg	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	26.0	2.0	28.0	-11.2
Portugal	0.0	1.7	0.0	1.7	-13.0
Spain	0.0	9.0	0.0	9.0	-13.0
Sweden	0.0	2.2	0.1	2.3	-12.0
United Kingdom	89.6	12.3	0.0	101.9	7.0
EU 15	239.6	119.9	4.2	363.7	1.5

Table 3.7. Emissions of N<sub>2</sub>O in 2010 with implemented (before 2000) abatement.

	Adipic acid (kt)	Nitric acid (kt)	Other processes (kt)	Total (kt)	Change from 1990 (%)
Austria	0.0	0.5	0.0	0.5	-13.0
Belgium	0.0	8.8	1.7	10.5	-8.8
Denmark	0.0	0.0	0.0	0.0	0.0
Finland	0.0	2.6	0.0	2.6	-13.0
France	1.2	31.9	0.1	33.2	-63.1
Germany	3.7	13.2	0.0	16.9	-79.6
Greece	0.0	1.8	0.3	2.1	-9.0
Ireland	0.0	2.3	0.0	2.3	-13.0
Italy	16.3	7.6	0.0	23.9	1.7
Luxembourg	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	26.0	2.0	28.0	-11.2
Portugal	0.0	1.7	0.0	1.7	-13.0
Spain	0.0	9.0	0.0	9.0	-13.0
Sweden	0.0	2.2	0.1	2.3	-12.0
United Kingdom	5.4	12.3	0.0	17.6	-81.5
EU 15	26.6	119.9	4.2	150.7	-57.9

### 3.5 AGGREGATION OF OPTIONS

The two options available for implementation by 2010 are abatement of adipic acid emissions and of nitric acid emissions using SCR; abatement in the process gases for nitric acid plant appears more advanced than end of pipe technology. The costs are as shown in Table 3.3 and Table 3.4. The additional reductions available from these two options (compared to the implemented abatement shown in Table 3.7) are shown in Table 3.8.

Table 3.8. Additional Reductions from Application of Abatement Options

	<b>Adipic acid production (kt N<sub>2</sub>O)</b>	<b>Nitric acid production (kt N<sub>2</sub>O)</b>
Austria		0.4
Belgium		7.0
Denmark		0.0
Finland		2.1
France		25.5
Germany		10.6
Greece		1.4
Ireland		1.8
Italy	15.5	6.1
Luxembourg		0.0
Netherlands		20.8
Portugal		1.4
Spain		7.2
Sweden		1.8
United Kingdom		9.8
<b>EU 15</b>	<b>15.5</b>	<b>95.9</b>

## 4. CONCLUSION

In this study the potential for energy efficiency improvements are determined at the industrial subsector level. Only emission reduction options are included that have a high probability of being commercially available before 2010. In 2010 an emission reduction potential of 533 Mt of CO<sub>2</sub> has been identified. A further 467 Mt of CO<sub>2</sub> equivalent is avoided because electricity is consumed in 2010 with a lower emission factor than in 1990 (see also energy supply section). Total direct and indirect emission reduction amounts therefore to 1000 Mt of CO<sub>2</sub> equivalent.

Table 4.1 gives an overview of the investment costs, the yearly costs (sum of operation and maintenance costs and savings), average specific mitigation costs and potential for options applicable in the industry. The specific costs are calculated using a real interest rate of 4% and using the lifetime of the option, i.e. equipment. Options reducing fluorinated gases (HFCs, PFCs and SF<sub>6</sub> are discussed in another report<sup>49</sup>, but Table 4.2 gives the same information but categorized in four costs brackets.

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<sup>49</sup> “Economic Evaluation of Emission Reductions of HFCs, PFCs and SF<sub>6</sub> in Europe”, J. Harnisch and C. Hendriks, Ecofys, March 2000. Note that EAA considers PFC reduction potential by conversion of SWPB cells as overestimates because the total emission from EU primary smelters is 6-7 Mt CO<sub>2</sub> equivalent, and the potential from conversion of SWPB smelters is not more than half of this. EAA also considers the cost of conversion too low.

Table 4.1. EU15-average costs and total potential (Mt of CO<sub>2</sub>) for industrial emission reduction options in the EU15.

Pollutant	Measure Name	Sector	Emission reduction	Investment	Yearly costs	Lifetime	Specific abatement costs	
			Mt CO <sub>2</sub> eq.	euro/CO <sub>2</sub> eq.	euro/CO <sub>2</sub> eq.	year	euro/CO <sub>2</sub> eq.	
CO <sub>2</sub>	Application of continuous casting	Integrated iron and steel plant	1	557	-280	15	-230	
	Improved process control	Minimills	2	284	-274	15	-76	
	Miscellaneous	Petrochemicals	0.5	187	-92	15	-75	
	Debottlenecking	Petrochemicals	6	187	-92	15	-75	
	Miscellaneous I (Low cost tranche)	Pulp	2	200	-47	15	-67	
	Miscellaneous II (High cost tranche)	Pulp	2	1973	-271	15	-58	
	Process integration, e.g. by applying pinch technology	Petrochemicals	0.3	187	-54	15	-56	
	Ceramics - new capacity	Ceramics	3	0	-71	15	-54	
	Miscellaneous I (Low cost tranche)	Other industry	54	200	-47	15	-53	
	Electricity savings	Glass	0.2	1151	-271	15	-50	
	Fractionation - various options	Petrochemicals	0.3	469	-92	15	-50	
	Miscellaneous I (Low cost tranche)	Other Chemicals	38	200	-47	15	-49	
	Food, beverages and tobacco - miscellaneous I (Low cost tranche)	Other Food	20	216	-66	15	-49	
	Miscellaneous	Ceramics	11	187	-92	15	-47	
	Glass - new capacity	Glass	0.4	0	-51	15	-45	
	Miscellaneous - building materials	Other Building materials	6	188	-63	15	-44	
	Raising cullet percentage in raw material	Glass	1	0	-44	15	-44	
	Paper - New capacity	Paper	8	0	-45	15	-43	
	Electricity savings	Cement	1	1151	-271	15	-39	
	Cement - new capacity	Cement	5	0	-41	15	-38	
	Process integration, e.g. by applying pinch technology	Fertilisers	0.1	187	-54	15	-37	
	Food, beverages and tobacco - miscellaneous II (High cost tranche)	Other Food	28	532	-62	15	-35	
	Miscellaneous I (Low cost tranche)	Paper	14	200	-47	15	-35	
	Reduce clinker content of cement	Cement	1	0	-34	15	-34	
	Improving wet process kilns	Cement	2	0	-34	15	-34	
	Use of waste derived fuels	Cement	3	7	-34	15	-33	
	Optimisation of heat recovery of clinker cooler	Cement	1	29	-34	15	-31	
	Pulverised coal injection up to 30% in the blast furnace (primary steel)	Integrated iron and steel plant	1	200	-48	15	-30	
	Efficient CO <sub>2</sub> -separation (e.g. by using membranes)	Fertilisers	0.03	281	-54	15	-29	
	Improved drying, e.g. condensing belt drying	Paper	1	52	-30	15	-28	
	Miscellaneous II (High cost tranche)	Paper	11	667	0	15	-26	
	Cracking furnace - various options	Petrochemicals	0.2	750	-90	15	-23	
	Miscellaneous II (High cost tranche)	Other industry	54	667	0	15	-22	
	Miscellaneous	Sugar	4	187	-92	15	-12	
	Other non-ferro metals - miscellaneous	Other non-ferro	10	385	-46	15	-11	
	Batch and cullet preheating	Glass	1	269	-35	15	-11	
	Miscellaneous II (High cost tranche)	Other Chemicals	33	667	0	15	-11	
	Application of multi-stage preheaters and pre-calciners	Cement	0.2	673	-70	15	-10	
	Pressing to higher consistency, e.g. by extended nip press (paper making)	Paper	5	267	-20	15	-9	
	Application of efficient evaporation processes (dairy)	Dairy	1	567	-31	15	-8	
	Reduced air requirements, e.g. by humidity control in paper machine drying hood	Paper	6	361	-21	15	-6	
	<b>Subtotal: Cost range &lt; 0 euro / t CO<sub>2</sub> eq.</b>			<b>334</b>				
	CO <sub>2</sub>	Integrated mills - new capacity	Integrated iron and steel plant	2	0	0	15	0
		Scrap preheating in electric arc furnaces (secondary steel)	Minimills	0.3	0	0	15	0
		Oxygen en fuel injection in electric arc furnaces (secondary steel)	Minimills	1	0	0	15	0
		Minimills - new capacity	Minimills	15	0	0	15	0
		Replacement of mercury and diaphragm processes by membrane electrolysis (chlorine)	Other chemicals	6	0	0	15	0
		Miscellaneous I (Low cost tranche)	Iron and steel	12	200	-47	15	2
		Refiner improvements	Pulp	1	752	-30	15	2
		Improved melting technique and furnace design	Glass	1	366	-29	15	4
Low pressure ammonia synthesis		Fertilisers	0.01	469	-37	15	5	
Fertilisers - new capacity		Fertilisers	0.2	469	-37	15	5	
Gas turbine integration		Fertilisers	0.2	750	-56	15	11	
<b>Subtotal: Cost range 0 &lt; 20 euro / t CO<sub>2</sub> eq.</b>			<b>38</b>					
CO <sub>2</sub>		Heat recovery in TMP	Pulp	7	79	30	15	31
	Thin slab casting techniques	Iron and steel	1	802	-39	15	33	
	Recovery of process gas from coke ovens, blast furnaces and basic oxygen furnaces (primary steel)	Integrated iron and steel plant	1	347	5	15	36	
	Miscellaneous II (High cost tranche)	Iron and steel	11	667	0	15	47	
	<b>Subtotal: Cost range 20 &lt; 50 euro / t CO<sub>2</sub> eq.</b>			<b>20</b>				
	Advanced reforming	Fertilisers	0.1	1218	-45	15	65	
	Retrofit existing Hall-Héroult process (e.g. alumina point-feeding, computer control)	Aluminium	0.5	6330	-274	15	72	
	Efficient production of low-temperature heat (heat recovery from high-temperature processes)	Integrated iron and steel plant	2	1694	-18	15	135	
Wettable cathode	Aluminium	0.4	18086	-274	15	328		
<b>Subtotal: Cost range &gt; 50 euro / t CO<sub>2</sub> eq.</b>			<b>3</b>					

Pollutant	Measure Name	Sector	Emission reduction	Investment	Yearly costs	Lifetime	Specific abatement costs
			Mt CO2 eq.	euro/CO2 eq.	euro/CO2 eq.	year	euro/CO2 eq.
N2O	Industrial processes: Adipic acid	Chemical industry	66	232	24	15	0.1
	Industrial processes: Nitric acid	Chemical industry	22	238	106	15	0.4
<b>Subtotal: Cost range 0 &lt; 20 euro /t CO2 eq.</b>			<b>89</b>				
HFC	Industrial refrigeration: hydrocarbons and NH3	Food, Drink & Tobacco	1	36	-12	-9	-9
	Subtotal: Cost range < 0 euro /t CO2 eq.			1			
	Oxidation of HFC-23	Chemical industry	7	1	0.1	15	0.2
	Foam PU-one component: hydrocarbons	Other industry	3	4	0	15	0.4
	Foam PU-pipe in pipe: pentane	Other industry	0.1	27	0	15	2
	Industrial food refrig.: hydrocarbons and NH3	Food, Drink & Tobacco	2	164	-12	15	3
	Foams XPS : carbon dioxide	Other industry	6	11	5	15	6
	Aerosols : hydrocarbons	Other industry	2	85	3	15	10
	Foam PU-spray: water	Other industry	1	6	18	15	18
	Subtotal: Cost range 0 < 20 euro /t CO2 eq.			23			
	Foam PU-flexible faced laminate: pentane	Other industry	1	11	20	15	21
	Foam PU-discontinuous panels: pentane	Other industry	1	45	23	15	27
	Foam PU-blocks: pentane	Other industry	1	104	18	15	27
	Foam PU-continuous panels: pentane	Other industry	0.2	13	31	15	32
	<b>Subtotal: Cost range 20 &lt; 50 euro /t CO2 eq.</b>			<b>2.6</b>			
	Foam PU-appliances: pentane	Other industry	0.2	107	54	15	63
	<b>Subtotal: Cost range &gt; 50 euro /t CO2 eq.</b>			<b>0.2</b>			
PFC	Aluminium: Side worked pre-baked anode cell (SWPB) conversion	Non-ferrous Metals	5	39	-6	15	-2
	Semiconductors: etch - alternative chemicals	Other industry	1	0	0	15	0.0
	Aluminium: Vertical stud Soderberg anode (VSS) retrofit	Non-ferrous Metals	0.3	39	-3	15	1
	Semiconductors: Chemical vapour deposition (CVD), NF3	Other industry	10	49	23	15	28
	Semiconductors: etch - oxidation	Other industry	3	79	71	15	79
<b>Subtotal: All cost ranges</b>			<b>20</b>				
SF6	Magnesium production: use of SO2 as protection gas	Non-ferrous Metals	3	4	0	15	0.3
	<b>Subtotal: Cost range 0 &lt; 20 euro /t CO2 eq.</b>			<b>3</b>			
Cost range < 0 euro /t CO2 eq.			340				
Cost range 0 < 20 euro /t CO2 eq.			153				
Cost range 20 < 50 euro /t CO2 eq.			33				
Cost range > 50 euro /t CO2 eq.			6				
<b>Total emission reduction potential</b>			<b>533</b>				

Table 4.2. Emission reduction potential for all greenhouse gases per industrial sector in 2010 compared to the frozen technology reference level (Mt CO<sub>2</sub>-eq.). The reduction potentials are given for four cost brackets.

Emission reduction (Mt CO2 eq.)	< 0 euro	0 - 20 euro	20 - 50 euro	> 50 euro	Total
Chemical	78	102	0	0	180
Food, beverage and tobacco	54	2	0	0	57
Iron and steel	3	29	13	2	49
Non-ferrous metals	15	3	0	1	19
Non-metallic minerals	33	1	0	0	34
Paper, pulp and printing	49	1	7	0	56
Other industry	108	15	13	3	139
<b>Total</b>	<b>340</b>	<b>153</b>	<b>33</b>	<b>6</b>	<b>533</b>

Figure 4.1 shows the share in emission reduction categorised in four cost brackets.

As Figure 4.1 shows total greenhouse gas emissions increase from about 1495 Mt CO<sub>2</sub> equivalent to ca. 2007 Mt CO<sub>2</sub> equivalent on 2010 in the frozen technology case. If all technically feasible emission reduction options are implemented, the total greenhouse gas emission level drops by about 1000 Mt to about 1000 Mt CO<sub>2</sub> equivalent in 2010. This is equivalent to a 50% decrease compared to the frozen technology emission level (see Figure 4.1) About 88% of this drop is due to reduced emissions of CO<sub>2</sub> of which roughly half is achieved in the energy supply sector and the other half by options that could be taken in the sector itself. About 65% of total emission reduction is achievable by options at net negative costs. Another 20% can be realised at low to moderate cost (less than €20/t CO<sub>2</sub> equivalent) while the remaining 15% involve higher costs.

The results of this study should be regarded as a first step in the determination of the potential of energy-efficiency improvement by industrial sector for each EU Member State. Future research should be directed at least at two aspects:

- (1) the country specification of the figures should be improved,
- (2) the scope of improvement measures should be broadened.

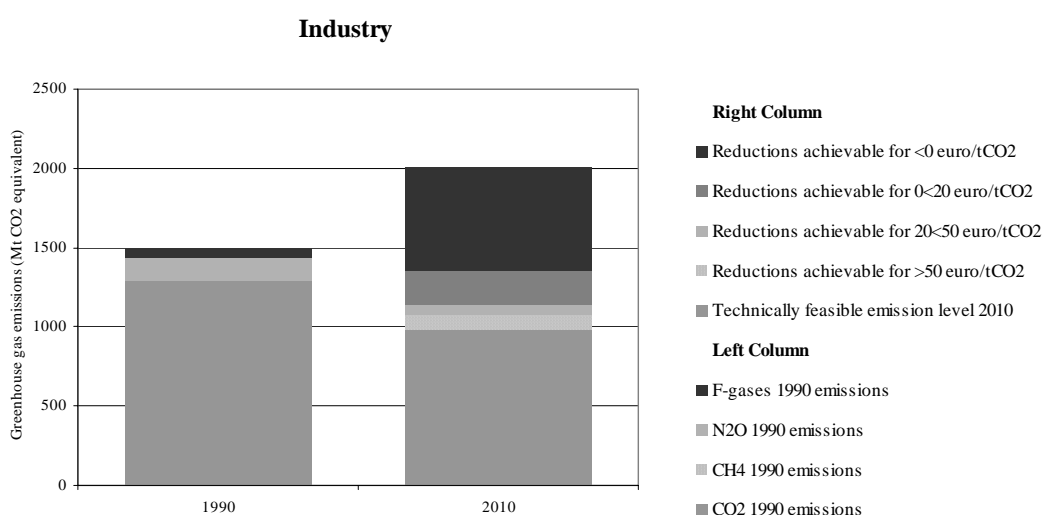
Improving the foundation of the figures can be obtained by:

- collecting and using more country specific production data, e.g. on product mix and structure of each sector and degree of implementation of techniques.
- collecting and using more specific energy data by making use of national statistical bureaux and national and international branch organisations.
- collecting more reliable data on investment cost by contacting suppliers of technologies. Also differences in contracting and implementation costs and personal costs between countries can be taking into account.

The scope of the improvement measures can be broadened by:

- considering options to improve the efficiency of material use, e.g. by recycling and re-use of materials.
- include more sectors, e.g. metal manufacturing, wood and textile industries.
- treat sectors in more detail; this is especially important for the chemical industries and non-ferrous metal industries.

Figure 4.1. 1990 base year emissions (left, by gas) and 2010 frozen technology reference level (right, by cost bracket).



The specific costs are calculated assuming a real interest rate of 4%. In all the cases the emissions are total emissions, i.e. direct emissions from the sector and

indirect emissions (emissions from steam and electricity production allocated to the sector). The emission reduction potential includes the emission reduction attainable in the energy supply sector which can be allocated to the industry, based on its steam and electricity consumption.

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### **Chapter 3**

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## ANNEX 1: EXAMPLE OF CALCULATION PROCEDURE

Name: Scrap preheating in electric arc furnaces (secondary steel)

Sector: Iron and steel

Subsector: Minimills

Required input data:

### 1. Specific Energy Consumption Electric arc furnaces per country:

*Specific energy consumption for EAF in 1990*

AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
GJ of electricity per tonne of liquid steel (GJ/tls)															
2.1	1.8	2.5	2.2	1.4	1.8	1.6	1.8	1.4	1.8	1.4	N/A	2.5	1.4	2.2	-
GJ of fuel per tonne of liquid steel (GJ/tls)															
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

<sup>1</sup> FRG only

### 2. Technical potential for energy efficiency improvement

See text in section 2.4.2

Saving on electricity demand: 80 kWh/tls = 0.30 GJ<sub>e</sub>/tls

Additional fuel demand: 0.2 GJ/tls

### 3. Maximum technical saving potential

This is derived by dividing the technical saving potential by the SEC.

AUT	BEL	DEU <sup>1</sup>	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE	EU
GJ of electricity per tonne of liquid steel (GJ/tls)															
14%	17%	12%	14%	21%	17%	19%	17%	21%	17%	21%	N/A	12%	21%	14%	-
GJ of fuel per tonne of liquid steel (GJ/tls)															
-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%

### 4. 1990 degree of implementation

The maximum technical saving potential calculated under 3 has to be corrected for the degree a measures has already been implemented in a country. For this measure these value is estimated at 0% for all countries.

### 5. Maximum degree of implementation

The maximum degree of implementation takes into account technical constraints for implementation. In the case of this measure implementation is often limited due to shortage of space. The maximum degree of implementation is therefore set at 10%.

## 6. Share of energy demand of subsector in that of the sector

*In the case of this measure minimills are the subsector and iron and steel is the sector. It is assumed that minimills are responsible for 100% of the bought electricity and for 1% of the fuel demand of the iron and steel sector.*

## 7. New capacity vs. old capacity

This measure only applies to old capacity. The potential has to be corrected for this.

The following table gives the new capacity in 2010 according to the baseline scenario in Primes.

AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
50%	53%	36%	0%	32%	0%	42%	48%	0%	28%	24%	100%	56%	39%	39%

The finale share in energy demand to which the measure applies is obtained by multiplying the share calculated under 6 by the old capacity (=1-new capacity). This gives:

AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
50%	47%	64%	100%	68%	100%	58%	52%	100%	72%	76%	0%	44%	61%	61%

## 8. The potential energy saving

The potential saving on fuel or electricity demand can now be determined as follows:

$$\text{annual potential saving} = (\text{implementation in 2010 (5)} - \text{implementation in 1990 (4)}) \\ \times \text{maximum technical saving (3)} \times \text{share (7)}$$

This results in the following potential electricity and fuel savings:

	AUT	BEL	DEU	DNK	ESP	FIN	FRA	GBR	GRC	IRL	ITA	LUX	NLD	PRT	SWE
Fuel	0.0%	0.0%	0.0%	0.0%	-2.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Electricity	0.7%	0.8%	0.6%	0.9%	2.1%	1.1%	1.9%	1.0%	1.1%	1.6%	0.0%	0.0%	0.0%	0.9%	0.8%

This savings are expressed as percentage of the fuel and electricity demand of the sector Iron and Steel in 2010, according to the baseline scenario in Primes.

## ANNEX 2: LIST OF PARTICIPANTS

### Participants at Experts Workshop “Industry” and “Commercial and Residential sector”, March 30 1999, DG Environment, Brussels

Name	Organisation
<i>Experts</i>	
Paul Ashford	Caleb Management Services Limited (EUROACE)
Rob Bradley	Energy specialist
Valérie Callaud	EUROPIA, Deputy Secretary General
Giovanni Cinti	Italcementi Group, C.T.G. S.p.A
Christine De Laeter	Dow Benelux NV Powerplant
Aymon de Reydellet	SAINT GOBAIN ISOVER, Environnement et risques industriels
Mats Fredriksson	Texaco
Graham Funnell	UK Steel Association
Anu Karessuo	Finnish Forest Industries Federation Environmental Manager
Paul Laffont	SAINT GOBAIN GLASS Dir. Environnement et Normalisation
Lars Nilsson	Lund University Department of environmental and energy systems studies
Erik Nordheim	European Aluminium Association
Stephan Singer	WWF European Policy Office
Helmut Warsch	Siemens
<i>Consultants</i>	
Judith Bates	AEA Technology Environment
Kornelis Blok	Ecofys Energy and Environment
Pantelis Capros	National Technical University of Athens
Jeroen de Beer	Ecofys Energy and Environment
Chris Hendriks	Ecofys Energy and Environment
<i>Commission staff</i>	
Timo Aaltonen	TREN.B.1
Suzanne Doschko	ENTR.E.1
Marc Hayden	ECFIN.E.4 Environmental policy, transport and energy
Peter Horrocks	ENV.D.3, Air quality, urban environment, noise, transport & energy
Daniel Johansson	European Commission ENTR.D.4 ICT & electronic commerce
Marco Loprieno	ENV.A2 Climate change unit
Stefan Lorenz-Meyer	ENTR.E.2
Åsa Malmstrom	ENTR.G.5
Aphrodite Mourelatou	European Environment Agency Energy and Environment project manager
Annika Nilsson	Commission DG ENV D.3
Norbert Theis	DG ENTR.E.3
Matti Vainio	ENV B.2, Economic analyses and employment

**Participants at Experts Workshop “Agriculture”  
November 24 1999, DG Environment, Brussels**

<b>Name</b>	<b>Organisation</b>
<b>Experts</b>	
Francisco de la Chesnaye	EPA, Climate Protection Division
Enzo Favoino	Gruppo di Studio sul Compostaggio della Scuola Agraria del Parco di Monza
Annette Freibauer	Institute of Energy Economics and the Rational Use of Energy
John Gale	IEA Greenhouse Gas R&D Programme
Philippe Gry	Grande Paroisse SA, Technical Department
Reid Harvey	EPA, Climate Protection Division
Gunnar Kongshaug	Fertilizer Technology Hydro Agri, Vice President
Jürgen Küsters	Hydro Agri Deutschland GmbH
Richard S.J. Tol	Free University, Institute for Environmental Studies
Alain Vasteels	Kemira SA
<b>Consultant</b>	
Judith Bates	AEA Technology Environment
David de Jager	Ecofys Energy and Environment
Chris Hendriks	Ecofys Energy and Environment
<b>Commission</b>	
Luis Carazo-Jimenez	European Commission, Environment DG D/01 “Water protection, soil conservation and agriculture”
Louis du Breil de Pontbriand	European Commission Agriculture DG F/13
Jean Duchemin	European Commission, Environment DG D/01
Joachim Ehrenberg	European Commission Entreprise DG C/04 “Chemicals, plastic and rubber”
Jane Feehan	Environment DG D/01., “Environment and agriculture”
Owen Jones	European Commission, Agriculture DG A/01
Daniel Mailliet	European Commission, Environment DG A/02 “Climate change”
Adelmo Moreale	European Commission, Agriculture DG F/22
Matti Vainio	European Commission, Environment DG B.2 Economic Analyses and employment
Peter Zapfel	European Commission, Economic and Financial Affairs DG E.4, “Environmental policy, transport and energy”