BUILDING THE COST CURVES FOR CO_2 STORAGE, PART 1: SOURCES OF CO_2

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Building the Cost Curves for CO_2 Storage, Part 1: Sources of CO_2

Background to the Study

The IEA Greenhouse Gas R&D Programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels. Much of the Programmes work has concentrated on emissions of carbon dioxide from power generation and particularly on techniques for capture and storage of CO_2. To date a series of studies have been undertaken, on a range of options for the storage of carbon dioxide. The options studied have included:

- storage of CO_2 in coal seams, with associated enhanced recovery of coal bed methane (ECBM),
- storage of CO_2 in deep saline reservoirs,
- storage of CO_2 in disused oil and gas reservoirs,
- storage of CO_2 in oil fields with associated enhanced oil recovery,
- extraction of methane from natural gas hydrates with subsequent storage of CO_2
- ocean storage of CO_2

The potential of particular mitigation options can be usefully expressed as abatement "cost-curves" - for example Figure 1 (below). These curves show the potential capacity for sequestration as a function of the cost of storage.

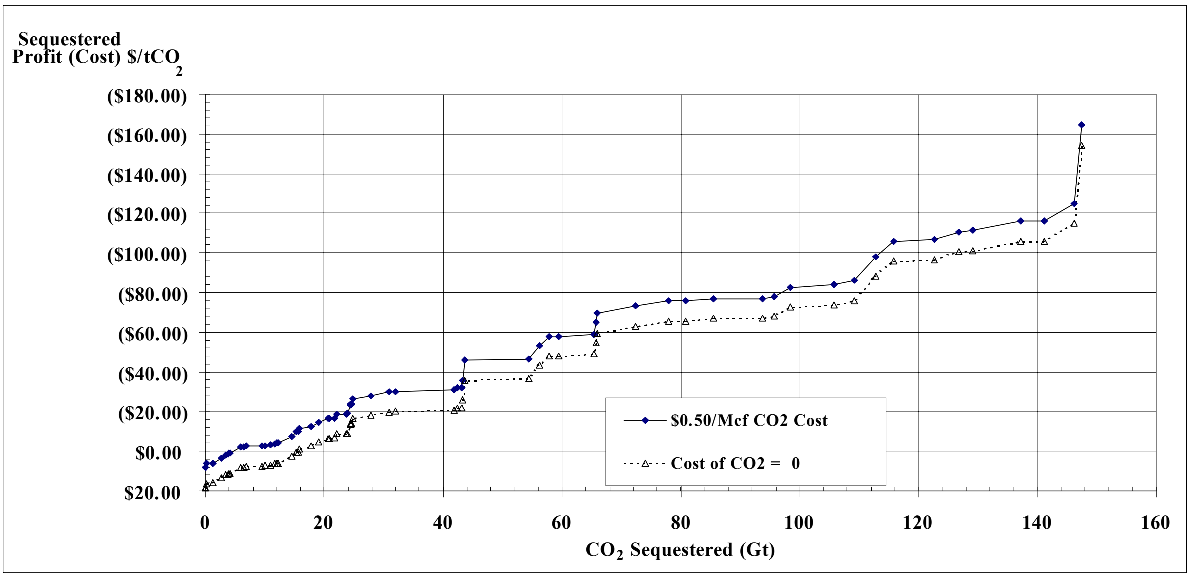

Figure 1 CO_2 Sequestration with ECBM Recovery in Major Worldwide Coal Basins[1].

However, IEA GHG does not have cost-curves for the whole chain of CO_2 capture, transmission and storage. The intention is that, in a series of studies, such data would now be assembled for all of the potential storage options on a common basis.

[1] Figure taken from Report PH3/3, 'Enhanced Coal Bed Methane Recovery with CO_2 Sequestration', August 1998.

The aim of this first study in the series is to look at the major sources of anthropogenic CO_2, assembling a global database of carbon dioxide emission sources detailing quantities and locations. The study will provide the basic data on sources of CO_2 for all subsequent studies in the series.

This study has been carried out by Ecofys of the Netherlands.

Technical Background

Any CO_2 capture and storage project involves three distinct components:

1. Capture of the emitted CO_2 from the source process followed by dehydration/compression
2. Transportation of the CO_2 by pipeline to the storage site,
3. Injection and storage of the CO_2 into the chosen reservoir.

In order to assess the attractiveness of CO_2 capture and storage as a mitigation option it is necessary to cost the entire process. However, to derive such an overall cost requires a judgement to be made on several issues, which include:

- The type of capture process that will be used - this can vary depending on the size of the source of the CO_2 and the purity of the CO_2.
- The distance the CO_2 needs to be transported, the terrain over which it will travel and whether it is onshore or offshore.
- The type of storage reservoir to be used, its siting (i.e. onshore or offshore) and whether there is any existing infrastructure that can be re-utilised.

IEA GHG is developing cost curves for geological storage in a series of stages on a regional basis. The initial selection of regions is those that are considered more likely to consider implementing the technology in the foreseeable future i.e. Western Europe, North America[2], Japan and Australia.

Each of the regional cost curves studies will consider a series of geological storage options that include:

- Deep saline reservoirs - open and closed structures both on and offshore,
- Depleted, disused and unexploited hydrocarbon reservoirs,
- Depleted hydrocarbon reservoirs that could be used for CO_2 enhanced oil recovery operations,
- Deep unminable coal seams that could be used for CO_2 enhanced coal bed methane recovery operations.

The first step is to develop a database of the anthropogenic emission sources of CO_2 globally and make projections of how these may develop in the foreseeable future. The CO_2 sources will include all stationary emission sources from which CO_2 could be captured for storage. Stationary sources include: power plants, refineries, other large industrial facilities and gas processing plants. Such stationary emission sources represent about 60% of global CO_2 emissions[3]. After this has been done, a series of regional studies will assemble data on the storage options. Finally the cost of transmission of CO_2[4] will be included to build regional and global cost-curves.

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[2] For the purposes of the study North America is considered to include both Canada and the USA.
[3] IEA World Energy Outlook 2000
[4] The transmission costs for CO_2 have been developed in a separate study by IEA GHG – Transmission of CO_2 and Energy, PH4/6, March 2002.

Results and Discussion

The following areas are described in this report:

- The CO_2 sources database - its contents and development.
- Projection of emissions to 2010 and 2020.

The CO_2 Sources Database, Contents and Development

A database of the major anthropogenic sources of CO_2 has been developed in the form of a Microsoft Excel spreadsheet (a Microsoft Access version is also available). The database contains some 14 641 entries and has collated data on current CO_2 emissions from: power plants, oil refineries, gas processing plants, major industrial sources (ammonia, cement, and iron and steel plants), hydrogen plants, ethylene and ethylene oxide plants. The cumulative world CO_2 emission from the 14 641 entries in the database was 13.44 Gt/y in 2000. The distribution of stationary CO_2 emission sources by industry sector is shown in Figure 2. Power plants dominate the statistics with 54% of all identified stationary CO_2 emission sources. The next highest category is the cement industry with 15% of all sources. The distribution of stationary CO_2 emission sources on a regional basis is shown in Figure 3. North America is the region with the largest number of stationary CO_2 sources (37%) followed by OECD Europe (14%) and China (10%).

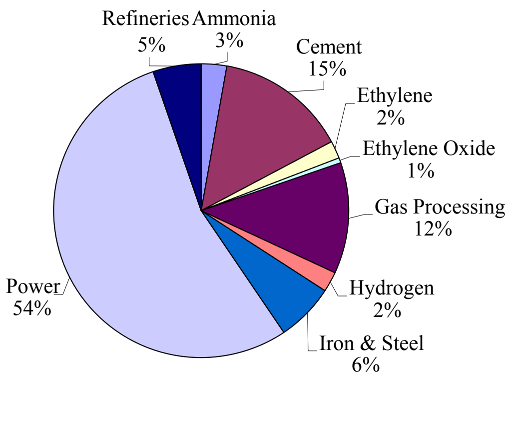

Figure 2 CO_2 Sources by Industry

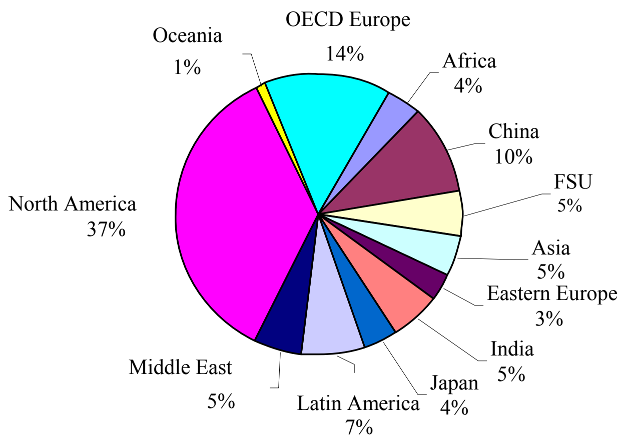

Figure 3 CO_2 Sources by Region

The data contained within the database has been compiled from a variety of publicly available and referencable sources. The data sources used in the study are summarised in the Table 1.

Table 1 Sources of Data Included in the Database

Identification of Emission Sources	Emissions Data
International Fertiliser Development Centre, World Cement Directory, World Electric Power Plant data base, Oil & Gas Journal (various surveys & databases), ChemExpo, Chemical Weekly	UK Environment Agency, Corinair[5] database, STF[6], ERL[7], CITEPA[8]

The data outlined in Table 1 was supplemented by data from the contractor's own databases, reports by other consultants (an example was an SRI Consulting Study – China Report 2001), the European Commission supported GESTCO project[9] and direct contacts with manufacturers such as BASF, Norsk Hydro and Aalborg Portland A/S.

The database contains information by plant name, company name, location (city, country, and region) latitude and longitude co-ordinates, annual CO_2 emissions (for base year) and CO_2 emission concentrations. Data on emissions concentrations at the plant level was found to be limited and, in some cases, had to be calculated e.g. for power plant emissions. The calculation methodology is given in the main report and in the database for reference purposes. This methodology is the one used in compiling statistics on national emission inventories. For some industrial operations, difficulties were encountered in obtaining emission statistics. For example, in the gas processing sector, only limited emissions data was found (most if it is from direct contact with the operators), nor was there much data available on the CO_2 content of the gas fields to allow the CO_2 emissions to be calculated. This represents a weakness in the database, which it is hoped can be rectified by additional data input at a later stage.

The latitude/longitude co-ordinates allow the data to be used in any Geographical Information System (GIS). The addition of the geographical co-ordinates to the database was achieved by retrieving the co-ordinates from the USGS[10] Geological Names Information System (GNIS). Overall, some 74% of the 14 641 entries could be located and their co-ordinates were entered in the database. Difficulties were experiencing in co-ordinating some of the sites with place names in the GNIS. On a regional basis the matching of co-ordinates was lowest in regions like East Asia (56%), India (62%) and Middle East (63%), due to difficulties in matching place names to the GNIS. Regions of high matching were Europe (83%) and North America (78%). Coverage for different industry sectors varied - for refineries, power generation and ethylene plants, 80 to 81% of the locations were matched. However, the lowest match (36%) was achieved for gas processing plants, where many small production sites could not be related to place names. The worst matching was in Canada where none of the listed 937 gas processing sources (representing 6% of the total sources) could be matched using the GNIS.

Since it was important that the data contained in the data base could be used in further studies, the data from the database on high purity CO_2 emission sources (100% CO_2) has been utilised in the IEA GHG study on Opportunities for Early Application of Capture and Storage of CO_2 (to be reported in PH4/10). It was found that the data on high purity sources was easily extracted from the database and loaded into a commercially available GIS software package, ArcView, for application in the Opportunities for Early Application study. This activity demonstrates that the data can be readily reutilised as planned.

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5 Corinair is a database of emissions from large point sources.
6 Norwegian pollutant release and transfer register
7 Dutch Emission Registry
8 Technical Centre for the Study of Atmospheric Pollution, France
9 The GESTCO project is a European Commission supported project that is mapping CO_2 sources and geological storage reservoirs in areas of Western Europe
10 United States Geological Survey

In addition, during the development of the database a number of checks were made to test the quality of the data, for example:

- The contractors on the Opportunities for Early Application study compared the total CO_2 emissions from the power generation and industrial sectors in the database with those in the World Energy Outlook and good agreement was observed. This gives confidence in the magnitude of the total emissions within the database.

- The study contractors checked the country data reported from several European national emissions inventories and compared these with the annual emissions calculated from the database. In addition, the emissions calculations used in the database were also compared with the data presented in the national inventories. In both cases good agreement was found.

Both activities give confidence that the database is accurate and can be readily utilised.

Projection of Emissions to 2010 and 2020

In the second part of the study, the location of future sources of CO_2 emissions were analysed and the magnitude of the CO_2 emission at each source estimated. For developed countries it was assumed that the infrastructure and industrial development were mature and that new capacity (if constructed at all) could be built in existing locations. For developing countries it was initially considered that new build would take place at sites different from those used for existing operations. A number of factors were considered to estimate where new plants could be built. However, after an analysis of recent power plant construction in India and China, it was found to be difficult to assign a set of criteria that might allow the location of new plant to be predicted with any degree of accuracy. Therefore, for the purposes of the study it was assumed that future increases capacity in these countries would be at existing locations; the additional capacity was then allocated over the current production sites.

To predict the likely emissions in 2010 and 2020, emissions at the existing sites were increased based on the expected growth rate for individual sectors[11]. The expected reduction of specific energy consumption for each sector was also factored in. Based on the growth projections, CO_2 emissions from all sources were estimated to grow by 36% in 2010 (to 18.24 Gt/y) from a base level of 13.44 Gt/y in 2000. In 2020, CO_2 emissions were projected to increase by 76% from the year 2000 baseline level to 23.31 Gt/y.

[11] Industry growth rates were based on available information sources such as World Energy Council Outlook, European Energy Outlook, World Energy Outlook, Energy Information Agency – International Energy Outlook, IEA Energy Policies for IEA Countries (2000) and USDOE Annual Energy Outlook statistics.

Expert Group Comments

The draft report on the study was sent to a panel of expert reviewers and a number of the IEA GHG Programme's members who had expressed interest in reviewing the study report. In general the report was well received by the reviewers, who felt that a substantial exercise had been completed by the contractor and that the database would act as a valuable reference tool for future use.

Several of the reviewers tested the data contained in the report, in particular the ease with which the data could be used to construct a GIS and expressed their opinion that the contractors had done a good job and that data entry is straightforward. In addition, a small number of reviewers cross checked the data on power plants and refineries in the USA and found good agreement between their databases and the study report. Once again these cross checks give confidence that the data contained in the database can be used effectively in the development of the planned future regional cost curve studies

Several reviewers recommended that every effort should be made to improve the coverage of the data within the database. It was considered that as much effort as possible should be put into acquiring latitude/longitude co-ordinates on all types of sources. It was acknowledged that the gas processing sector was the area that needed most work, but there may be problems in obtaining the data, which in many cases will be commercially sensitive.

Major Conclusions

An extensive database of CO_2 emission sources worldwide has been compiled from a variety of public domain information sources. Wherever possible every effort has been made to take data from verifiable and reputable data sources to ensure that the data contained within the data base is as accurate as possible. The database represents a significant first step in developing an understanding of the major CO_2 emission sources worldwide.

The database contains over 14 500 entries for power plants, large industrial plants, gas processing, ethylene/ethylene oxide plants and hydrogen plants and refineries. For each entry efforts have been made to assign latitude and longitude co-ordinates to allow the data points to be utilised with a GIS software package. It is acknowledged that there are some deficiencies in the database; in particular, the data on the gas processing sector has the lowest overall coverage with only 36% of the emission sources allocated latitude and longitude co-ordinates. There are gaps especially in the gas processing dataset. Addition of the co-ordinates for missing plant in the gas processing sector would increase coverage of the overall database from 74 to 80%.

One of the key objectives in developing the database was that the data contained therein could be readily used in later studies to develop regional cost curves for geological storage of CO_2. The data has already been utilised in a further study by the IEA GHG and was also tested by a number of the reviewers during the expert review stage. Both these activities indicate that the data can be considered as readily and easily utilisable for future work that the Programme and its members may wish to undertake.

Recommendations

The Programme should consider the most effective ways of improving the co-ordinate coverage within the database. Improving the CO_2 sources data should be part of the storage studies in the 4 regions to be examined initially, i.e. Europe, North America (including Canada), Japan and Australia. Improving the CO_2 source datasets in some of the developing country regions such as China, India, East Asia, and Latin America for example, will require local input and will have to be addressed separately.

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BUILDING THE COST CURVE FOR CO_2 STORAGE

SOURCES OF CO_2

Final report

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1 INTRODUCTION

The IEA Greenhouse Gas R&D Programme (IEA GHG) is systematically evaluating the cost and potential for reducing emissions of greenhouse gases arising from anthropogenic activities, especially the use of fossil fuels.
Up till now a number of studies have been carried out, focussing on different storage options for carbon dioxide. In these studies particular mitigation options are described and presented in so-called mitigation cost curves, which show the potential capacity for CO_2 sequestration as a function of the cost. However, not all possible storage options have been covered in the above-mentioned studies. Therefore, the IEA GHG has proposed a series of studies in order to be able to cover the whole range of storage options.

The study proposed here will act as a pre-study, focussing on the location (country, city, longitude-latitude co-ordinates) and size of large industrial anthropogenic CO_2 sources (kt of CO_2 per year). The inventory covers fossil-fuel fired power plants, chemical plants (ammonia, ethylene and ethylene oxide), refineries, iron and steel plants, cement plants, power plants and natural gas processing sites.

Since large-scale implementation of CO_2 removal and storage would take a substantial amount of time, not only information on current sources is required, but also on the location and size of future sources. Therefore also information on possible developments of anthropogenic sources of CO_2 up to 2010 and 2020 is required. A related issue is that economics of newly built plants are considerably better than retrofit plants because CO_2 removal is a capital intensive technology and integration of the recovery technology in a plant might considerably improve the efficiency of the plant.

The information on sources is obtained by using a large number of information sources, like databases and other types of inventories. In this report per industrial source a short description is given on the nature of the CO_2 emissions and on the information sources used and assumptions applied for the calculation of the emissions (section 3 to 11). Section 12 is dedicated to future development of CO_2 emissions. The results of inventory are laid down in a database (Excel and Access), which is separately delivered with this report.

2 STRUCTURE AND CONTENT OF DATABASE

The database (named *Database CO_2 sources*) provides information on large point sources per country worldwide. The database is available in Access (*Database CO_2 sources.mbd*) and Excel (*Database CO_2 sources.xls*).

2.1 INFORMATION IN DATABASE

Basically, the database contains information on the name and location of the plant, information on operation and production, and on annual emission of carbon dioxide. The location is also given in longitude and latitude co-ordinates. This allows to use the information in any GIS application (e.g. ArcView and MapInfo). A detailed description per sector on the collection of information, the sources of information used, and the omission in data collection is given in the sections 3 to 11 of this report. Table 2-1 gives the references of the information sources.

Table 2-2 shows the entries (field names) of the records (point sources) in the database. The table provides also a short description of each entry. Table 2-3 tabulates the industries included in the database. This table summarises also the number of plants per industry per region included in the database. In total almost15 thousand plants are included, of which almost 8 thousand are power plants. To identify the location of the CO_2 emission site more easily longitude/latitude co-ordinates are added to the database. This allows the user also to use the data in GIS supported software. The conversion has been done by retrieving the co-ordinates using GNIS (2001) and GNS (2001).[1] However, not in all cases the location name could be retrieved in the database. On average about 75% could be retrieved. The lowest coverage is for natural gas fields, with many small production sites with location names not related to city names (see Table 2-4 and Table 2-5). From the last table it can be seen that especially the coverage of longitude/latitude co-ordinates in (East) Asia is low (about 50%). Probably in most cases different spelling of city name is the main cause.

Annex 1 presents various example graphs with cross sections of the database. Graph 1 to 6 shows for the European OECD countries the point sources per type of industry. For the power plants an additional graph is added in which the size of the point source is depicted. Graph 7 displays all point sources worldwide included in the database.

[1] A geographic database containing city names and their corresponding geographic coordinates was used to look up the coordinates of the CO2 point sources. The geographic database was set up by using data from the US Geological Survey's Geological Names Information System (GNIS) and from the US National Imagery and Mapping Agency's GEOnet Names Server (GNS). The GNIS and the GNS are the official repository of domestic and foreign geographic names information of the US.

Table 2-1. References to data information sources

Reference code	Description of information source
Aalborg Portland A/S	Statement from Aalborg Portland A/S
BASF	Statement from BASF
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Germany)
Ceweb	Www.chemexpo.com
CITEPA	Technical Center for the Study of Atmospheric Pollution (France)
Corinair	Corinair emission database on large point sources
Crdoc	China Report: Chemical Product Trends, Ethylene Oxide (SRI consulting, 2000)
Cwweb	Www.chemweek.com
DEA	Danish Energy Agency
Egrid	E-grid 2000
ERL	Dutch Emissie Registratie Lucht
IFDC	International Fertilizer Development Center
IGME	Institute of Geology and Mineral Eploitation (Greece)
Norsk Hydro	Statement from Lars Ingolf Eide, Norsk Hydro
OGJethdoc	Oil & Gas Journal Ethylene Report 2001
OGJgasproc	Oil & Gas Journal Gas Processing Survey 2001
OGJrefdoc	Oil & Gas Journal Worldwide Refining Survey 1999
OGJwwcdoc	Oil & Gas Journal Worldwide Construction 2001
STF	Statens forurensingstilsyn (Norwegian Pollutant Release and Transfer Register)
UKEA	UK Environment Agency
WCD	World Cement Directory - Cembureau
WEPPdb	World Electric Power Plant database

Table 2-2. Structure of Database CO_2 Sources

	Field name	**Description of field content**
1	Source number	individual plant identification number
2	Sector	Industrial sector
3	Name of company	-
4	Plant name	-
5	Zip code	-
6	City	-
7	State/Province	
8	Country (EDGAR)[2]	EDGAR country name standard
9	Country code (EDGAR)	EDGAR country code name standard
10	Country code (NIMA)	Code needed for geo-matching; NIMA[3] standard
11	Region (EDGAR)	EDGAR region name standard
12	Latitude	Decimal numbers
13	Longitude	Decimal numbers
14	Match result	# geo-matching results
15	Status	Operational (OPR), planned (PLN), under construction (CON), retired (RET), mothballed (MOT)
16	Start-up Year	First year of operation
17	Retirement year	Last year of operation
18	CO_2 reported (Gg)	Emission reported by company or national environmental agency
19	Year of report	The reported year of CO_2 emission (reported emission)
20	CO_2 estimated (Gg)	Emission estimated with emission factor
21	Year of estimate	The reported year of CO_2 emission (estimated emission)
22	Concentration of CO_2 in flue gas %	Estimated concentration of CO_2 in flue gas
23	Product mix	Indication of the products of the plant
24	Energy consumption	Annual energy consumption (not yet available)
25	Unit of energy consumption	-
26	Production	Annual production (not yet available)
27	Unit of production	-
28	Full load hours (h)	Full load hours or capacity factor
29	Capacity	Reported production capacity of plant
30	Unit of capacity	-
31	Emission factor	Value or link to other sheet within workbook
32	Technology	Indication of technologies used in the plant
33	Fuel class	coal, oil, gas, biomass and waste, unknown
34	Main fuel	more detailed description of fuel (e.g. lignite, coke oven gas)
35	Other fuels	more detailed description of fuel (e.g. lignite, coke oven gas)
36	Company type	private or public
37	Quality of information (A,B,C,D,E)	Indication of quality of the data
38	Information source for the *reported emission*	-
39	Information source for *other entries*	-
40	Last updated (date)	Last date the entry has been updated
41	Remarks	Additional remarks
42	CO_2 2010 (Gg)	Projected emission in 2010 following a growth scenario
43	CO_2 2020 (Gg)	Projected emission in 2020 following a growth scenario
44	Prod. Growth 2010	Projected emission growth in 2010
45	Prod. Growth 2020	Projected emission growth in 2020
46	fuel type number	Number of fuel type referring to (main) type of fuel used.

[2] Emission database for global atmoshperic research of the RIVM and TNO, the Netherlands
[3] The US National Imagery and Mapping Agency (NIMA)

Table 2-3. Industries categories included in Database CO_2 sources and number of point sources per industry category and per region.

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processing	Hydrogen	Iron & steel	Power	Refineries	Total
Africa	19	134	6		38	7	41	263	51	**559**
Canada	9	20	5	3	937	12	24	129	23	**1162**
China Region	74	592	29	16	2	3	101	593	88	**1498**
CIS (including Baltic states)	34	96	24		32	10	59	421	68	**744**
East Asia	12	126	20	6	21	19	65	382	32	**683**
Eastern Europe	23	84	14		10	9	47	251	32	**470**
India Region	60	187	15	2	26	4	47	426	32	**799**
Japan	9	45	13	5		45	70	357	35	**579**
Latin America	22	207	21	9	70	23	85	493	84	**1014**
Middle East	23	155	18	5	53	23	36	436	54	**803**
North America (rest)								2		**2**
Oceania	7	20	3		8	2	12	129	11	**192**
OECD Europe	68	349	55	15	45	50	217	1171	99	**2069**
USA	38	121	39	13	584	87	136	2903	156	**4077**
Total locations	**398**	**2136**	**262**	**74**	**1826**	**294**	**940**	**7956**	**765**	**14651**

Table 2-4. Based on number of point sources: coverage of co-ordinates by industrial category and region, (first table). Missing percentage of co-ordinates by industrial category and region (second table).

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processing	Hydrogen	Iron & steel	Power	Refineries	Total
Africa	95%	83%	83%		18%	86%	71%	71%	76%	**72%**
Canada	100%	80%	80%	33%	0%	92%	88%	84%	78%	**16%**
China Region	78%	77%	66%	81%	0%	33%	68%	57%	81%	**68%**
CIS (including Baltic states)	71%	69%	88%		3%	90%	59%	70%	50%	**65%**
East Asia	67%	61%	55%	17%	67%	89%	52%	51%	81%	**56%**
Eastern Europe	91%	87%	100%		80%	89%	85%	83%	91%	**86%**
India Region	65%	56%	73%	50%	69%	75%	74%	61%	78%	**62%**
Japan	100%	69%	92%	20%		91%	46%	76%	94%	**74%**
Latin America	77%	86%	86%	56%	69%	74%	82%	80%	80%	**80%**
Middle East	70%	77%	56%	40%	26%	57%	58%	63%	69%	**63%**
North America (rest)								100%		**100%**
Oceania	86%	90%	100%		63%	100%	83%	79%	91%	**81%**
OECD Europe	85%	84%	93%	93%	56%	90%	84%	76%	82%	**79%**
USA	71%	84%	85%	85%	89%	90%	88%	100%	90%	**96%**
Total locations	**78%**	**77%**	**81%**	**66%**	**36%**	**85%**	**74%**	**81%**	**80%**	**74%**

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processing	Hydrogen	Iron & steel	Power	Refineries	Total
Africa	5%	17%	17%		82%	14%	29%	29%	24%	**28%**
Canada	0%	20%	20%	67%	100%	8%	13%	16%	22%	**84%**
China Region	22%	23%	34%	19%	100%	67%	32%	43%	19%	**32%**
CIS (including Baltic states)	29%	31%	13%		97%	10%	41%	30%	50%	**35%**
East Asia	33%	39%	45%	83%	33%	11%	48%	49%	19%	**44%**
Eastern Europe	9%	13%	0%		20%	11%	15%	17%	9%	**14%**
India Region	35%	44%	27%	50%	31%	25%	26%	39%	22%	**38%**
Japan	0%	31%	8%	80%		9%	54%	24%	6%	**26%**
Latin America	23%	14%	14%	44%	31%	26%	18%	20%	20%	**20%**
Middle East	30%	23%	44%	60%	74%	43%	42%	37%	31%	**37%**
North America (rest)								0%		**0%**
Oceania	14%	10%	0%		38%	0%	17%	21%	9%	**19%**
OECD Europe	15%	16%	7%	7%	44%	10%	16%	24%	18%	**21%**
USA	29%	16%	15%	15%	11%	10%	13%	0%	10%	**4%**
Total locations	**22%**	**23%**	**19%**	**34%**	**64%**	**15%**	**26%**	**19%**	**20%**	**26%**

Table 2-5. Coverage of co-ordinates by industrial category and region, based on estimated CO_2 emission.

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processin	Hydrogen	Iron & steel	Power	Refineries	Total
Africa	90%	78%	80%			96%	84%	88%	82%	**86%**
Canada	100%	84%	86%	38%	2%	92%	83%	89%	70%	**83%**
China Region	82%	63%	53%	72%		27%	64%	59%	82%	**59%**
CIS (including Baltic states)	83%	69%	89%		0%	90%	53%	69%	58%	**67%**
East Asia	59%	38%	55%	10%	81%	89%	34%	50%	87%	**53%**
Eastern Europe	95%	85%	100%		64%	89%	84%	81%	95%	**82%**
India Region	73%	54%	71%	61%		64%	69%	71%	81%	**70%**
Japan	100%	66%	94%	37%		82%	3%	79%	94%	**73%**
Latin America	59%	89%	75%	35%	80%	42%	93%	86%	75%	**84%**
Middle East	75%	78%	52%	68%		56%	74%	71%	66%	**70%**
North America (rest)								100%		**100%**
Oceania	73%	90%	100%		61%	100%	97%	81%	93%	**83%**
OECD Europe	76%	81%	91%	80%	46%	95%	97%	74%	81%	**78%**
USA	87%	89%	83%	75%		89%	70%	100%	90%	**98%**
Total locations	**80%**	**71%**	**77%**	**63%**	**68%**	**81%**	**68%**	**75%**	**80%**	**75%**

3 AMMONIA PRODUCTION

Ammonia production can be subdivided into three classes: production from steam reforming (worldwide covering about 83% of the production)[4], production from partial oxidation (about 17% of the production)[5], and production from water electrolyses (less than 1% of the production). About 80% of the ammonia is used in the production of fertilisers. The remaining is used for various applications like the production of caprolactam, acrylonitrile, aniline , alkanolamines, etc. [BAT, 1997].

In steam reforming CO_2 is produced during the ammonia production through a chain of reactions:

1. Natural gas is reacted with steam over a catalyst to produce hydrogen and carbon monoxide. This is normally done at two reforming stages. The heat is supplied by burning natural gas (or other gaseous fuels) in burners.
2. The carbon monoxide is further converted with steam in a shift reactor to produce carbon dioxide and an additional amount of hydrogen.
3. The carbon dioxide is subsequently removed from the hydrogen. The hydrogen is used to produce ammonia by reacting it with nitrogen from air.

Two CO_2 streams can be identified: the flue gas stream of the burners, with a CO_2 concentration of typically around 8%, and the pure CO_2 stream. Another emerging technique is the pressure swing adsorption (PSA). This process may be used where the CO_2 purity has no priority. However, if pure CO_2 is needed, then it can be recovered by a classical solvent scrubbing process of the low-pressure off-gas of the PSA.

The removed CO_2 is either vented to the atmosphere or used in other products, mainly for the production of urea.

3.1 AVAILABLE INFORMATION

Emissions on plant level are only available for a few countries. Emissions of CO_2 are therefore estimated by using capacity data of ammonia production. A comprehensive inventory of ammonia plants has been made by the IFDC (International Fertilizer Development Center), which compiled a database containing data on plant name, company name, location (country and city) and capacity. The database contains historical information on capacity for 1998 to 2000 and projected data for 2001 to 2004. In some cases additional information is given, e.g. the year of closure of the plant. Unfortunately, no information was given on fuel use.

An important use of the produced CO_2 is urea production. The urea is formed by dehydrating the ammonium carbamate. Carbamate is produced by a reaction of CO_2 with ammonia. As this amount of CO_2 is used for urea production and not vented to the atmos-

[4] from which 77% natural gas, and 6% naphtha, LPG, and refinery gas.

[5] from which 14% coal and cokes and 3% heavy hydrocarbon fractions.

phere it will not be available for CO_2 sequestration projects. For this uptake a correction has been made. Data on production of urea on plant level has been provided by IFDC.

3.2 CALCULATION OF EMISSION OF CARBON DIOXIDE

The emission of CO_2 is calculated per location, i.e. the total of the emissions for all ammonia plants on the same location subtracted with the uptake of CO_2 in urea plants at the same location.

The production of CO_2 per plant is calculated by multiplying the capacity of a plant by an utilisation factor and an emission factor. The utilisation factor is assumed to be 92% (8000 hours full load). The emission factor for an ammonia steam reforming plants is 1.2 kg per kg ammonia produced. For a partial oxidation plant using coal as a fuel the emission factor is typically 3.8 kg per ammonia [BAT, 1997]. Assumed is that all plants use natural gas as feedstock, except for the plants in China, which generally use coal as a feedstock. The CO_2 used in urea plants varies typically between 1.0 and 1.5 kg per kg of urea. We use a factor of 1.4 kg/kg.

3.3 COVERAGE OF EMISSION IN THE DATABASE

The IFDC database covers all plants worldwide. For about 80% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.

4 HYDROGEN PRODUCTION

Industry produces H_2 by steam reforming or partial oxidation (gasification). In these processes, hydrocarbon feed reacts with oxygen at high temperatures to produce a mixture of H_2, CO, CO_2 and CH_4. Impurities such as CO_2 are removed from the process stream to obtain pure H_2. In some purification techniques this results in a pure stream of CO_2.

Hydrogen plants fall into two groups depending on the type of CO_2 removal system. Plants built since the late 1980s tend to use pressure swing adsorption (PSA) for purification, while older facilities use wet scrubbing. After separation of hydrogen, the remaining (fuel) stream has a CO_2 concentration of typically around 50%. This fuel is redirected to the reforming section, where it is combusted. The resulting CO_2 in the flue may be 20% or higher [Foster Wheeler, 2001]. In case CO_2 is required pure, the intermediate stream can be purified before the fuel is redirected to the reformer. The system with wet scrubbing results directly in a high purity CO_2 stream.

4.1 Available information

Refineries and producers of industrial gases produce hydrogen. In general, the pure CO_2 stream (>99 vol%) is vented on refineries, whereas for industrial gases producers it is a useful product and normally not vented. In this inventory therefore, only hydrogen production from refineries were considered.

The Oil & Gas Journal published the 1999 Worldwide Refining Survey [Oil & Gas journal, 1999] which amongst others covers the worldwide hydrogen production capacity on a plant level. It also describes the production or purification technology.

For the Netherlands, emissions were reported by the national emission agency: Emission Registratie Lucht (ERL) for the year 1998. In all other cases the emissions were calculated as described below.

Information on new plants was available from the OGJ survey: Worldwide Construction 2001 [Oil & Gas Journal, 2001].

4.2 Calculation of emission of carbon dioxide

The OGJ Refining Survey [Oil & Gas journal, 1999] describes different production technologies; these are listed in Table 4-1, together with their respective emission factor and the CO_2 concentration in the off gases. An utilisation factor of 80% of capacity was assumed.

Table 4-1 Emission factors and CO_2 concentration for different hydrogen production technologies

Technology	Emission factor kg CO_2/kg H_2	Concentration CO_2 in flue gas
Steam methane reforming[1]	4.0	100%
Steam naphtha reforming[1]	5.2	100%
Partial oxidation	8.3	100%
PSA	4.0-8.3	8-14%
Steam methane reforming[1] + PSA	4.0	8-14%
Cryogenic	4.0-8.3	100%
Membrane	4.0-8.3	100%
Other	4.0-8.3	8-100%

[1] External combustion is assumed

4.3 COVERAGE OF EMISSION IN THE DATABASE

294 plants are included in the database located worldwide. For 85% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.

It is difficult to estimate the coverage of the hydrogen production by the database, because no worldwide data on hydrogen production and related emissions were available.

5 ETHYLENE

The bulk of industrial ethylene is produced in crackers requiring high levels of energy. CO_2 emission is caused by combustion of gas oil and/or naphtha resulting in a CO_2 concentration of 10-15%. A small fraction of the emission is a pure stream of CO_2 (>99%).

5.1 AVAILABLE INFORMATION

Data on ethylene production was available from the Ethylene Report [Oil & Gas Journal Ethylene, 2001], the OGJ Worldwide Construction [Oil & Gas Journal, 2001] and from the ChemExpo website [ChemExpo, 2000]. Operator, location and production capacities were listed here.

5.2 CALCULATION OF EMISSION OF CARBON DIOXIDE

Emissions were calculated based on production figures and emissions factors, as no emission data were available. An utilisation rate of 90% of capacity was assumed.

The CO_2 emission factor from naphtha and gas oil is assumed to be 72.6 tonne of CO_2 per GJ [AEA Technology, 1999]. The specific energy consumption for different regions is shown in Table 5-1 with the resulting emission factor for ethylene production.

Table 5-1 Specific energy consumption (GJ/t ethylene) and resulting CO_2 emission factor (kg CO_2/kg ethylene).

Region	SEC (GJ/t ethylene)	Emission factor (kg CO_2/kg ethylene)
Australia, Canada	34.0	2.47
Austria, Switzerland	33.9	2.46
Belgium	34.9	2.53
France	33.7	2.45
Germany	25.1	1.82
Japan, South Korea, Taiwan	25.4	1.85
Mediterranean Europe	32.5	2.36
Netherlands	33.6	2.44
Other	35.0	2.54
Poland	28.8	2.09
South America	32.8	2.38
UK and Scandinavia	34.5	2.51
USA	33.5	2.43

5.3 COVERAGE OF EMISSION IN THE DATABASE

262 plants are included in the database located worldwide. For 81% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.

It is difficult to estimate the coverage of the hydrogen production by the database, because no worldwide data on hydrogen production and related emissions are available.

6 ETHYLENE OXIDE

The principle use of ethylene oxide is in the manufacture of ethylene glycol and higher alcohols which find important applications in automotive antifreeze, explosives, cellophane, polyester resins, synthetic fibres and rubbers, and hydraulic fluids, The higher alcohols such as di- and tri- are used as plasticizers, humectants, lubricants, and solvents. It is an important intermediate in the manufacture of glycol ether solvents, ethanolamines and nonionic detergents.

Ethylene oxide (EO) is formed by reacting gaseous ethylene and oxygen over a solid catalyst. The main by-products are carbon dioxide and water. The ratio between the two reactions (i.e. formation of EO on the one hand and formation of CO_2 and H_2O on the other hand) is mainly determined by the catalyst used. CO_2 is removed and either vented or used.

6.1 Available information

Plant level EO data was gathered from the ChemWeek website [ChemWeek, 2001], from China Report: Chemical Product Trends, Ethylene Oxide [SRI consulting, 2000] and added capacity from OGJ Worldwide Construction 2001 [Oil & Gas Journal, 2001]: operator, location and capacity.

6.2 Calculation of emission of carbon dioxide

A selectivity of 0.80 kg EO per kg ethylene is assumed [IPPC, 2000], resulting in an average emission factor of 0.51 kg CO_2 per kg ethylene oxide. A capacity factor of 80% was assumed.

6.3 Coverage of emission in the database

74 plants are included in the database located worldwide. For 66% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.

In 1999 world consumption of EO was 12 Mt. The database covers a production capacity of 14.3 Mt, which results in a production of 11.4 Mt (capacity factor 80%). The coverage is estimated at 95%.

ECOFYS

7 OIL AND GAS PRODUCTION

Much of the CO_2 emitted from gas processing installations is that associated with the raw produced gas. For this reason the estimates for CO_2 emissions from this industry are limited to estimates of emitted associated gas.

7.1 Available information

The data for the gas processing industry was sourced from the Oil and Gas Journal June 25th, 2001; the World-wide gas processing edition. This data covers the production and capacity measurements of all processing facilities in the world from the year 2000. The volumes were reported in MMcfd which was converted to cubic meters per year using a conversion factor of $10.34*10^6$.

7.2 Calculation of emission of carbon dioxide

In this study the amount of CO_2 emitted at a gas processing installation is estimated as being that which is gas associated. The concentration of CO_2 depends on the contents of the gas processed. The difference in CO_2 fractions in raw natural gas between different gas wells, even those producing from the same field, is very large. For this reason it is not useful to make precise estimates for emissions. However, a first approximation for an emission value per installation was made using country average CO_2 content of produced gas [WEC, 95].[6]

Specific data for the CO_2 contents per gas field are not publicly available for competitive reasons. For example, AGSO – Geo-science Australia, compiled these data for Australia, but are not authorised to provide them to third parties.

7.3 Coverage of emission in the database

1826 production sites worldwide are included in the database. For only 36% of the production sites the longitude/latitude co-ordinates could be identified, because often no regular city or area name was available.[7] See Table 2-4 and Table 2-5 for detailed regional coverage.

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[6] Average CO_2 composition of gas in the following countries was sourced from the WEC, Survey of Energy Resources, 1995: Argentina, Australia, Austria, Bangladesh, Bolivia, Brazil, Bulgaria, Canada, Colombia, Croatia, Denmark, Ecuador, Finland, France, Germany, Hungary, Indonesia, Ireland, Japan, Jordan, Kyrgyzstan, Malaysia, Mexico, Namibia, Nepal, Netherlands, New Zealand, Slovakia, Spain, Switzerland, Taiwan, Tanzania, Turkey, UK and the Ukraine.
For the remaining countries (Algeria, Angola, Azerbaijan, Bahrain, Belgium, Brunei, Chile, China, Egypt, Estonia, Greece, India, Iran, Israel, Italy, Kazakhstan, Kuwait, Latvia, Libya, Lithuania, Mozambique, Nigeria, Norway, Oman, Pakistan, Peru, Poland, Qatar, Romania, Russia, Saudi Arabia, Syria, Thailand, Trinidad and Tobago, Tunisia, United Arab Emirates, Uzbekistan, USA, Vietnam, Venezuela, Yemen, Yugoslavia) no emissions were estimated due to the scope for error.

[7] Especially for Canada, China region and CIS countries the coverage of coordinates is very low.

In the year 2000 world production of gas was about 2422 billion cubic meters [BP Amoco Energy statistics, 2000]. The gas processing facilities covered in the database produced about 1460 billion cubic metres. The coverage is therefore estimated at about 60%.

8 REFINERIES

The main sources of CO_2 on refineries are power plants, furnaces and boilers, flares and process vent emissions. Around 2% of emissions stem from hydrogen production. The concentration of CO_2 in the flue gases is typically 3% for gas turbines, 13% for other combustion equipment and >99% for hydrogen production. The total CO_2 emission varies with the level of complexity of the plant.

8.1 AVAILABLE INFORMATION

Plant level data on operator, location and production capacity was available through the OGJ 1999 Worldwide Refining Survey [Oil & Gas Journal, 1999]. For Norway, national emission authorities reported UK, DENMARK and the Netherlands actual emission data. For other countries CO_2 emission was calculated based on emission factor.

8.2 CALCULATION OF EMISSION OF CARBON DIOXIDE

The CO_2 emission factor of a refinery is calculated by its fuel mix. An average refinery fuel mix is calculated based on a UK refinery, resulting in an emission factor of 0.22 kg CO_2 per kg output according to [AEA Technology, 1999]. An utilisation rate of 95% of the capacity was assumed.

8.3 COVERAGE OF EMISSION IN THE DATABASE

765 plants are included in the database located worldwide. For 80% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.
The Oil & Gas Journal Refining Survey covers world wide refining capacity.

9 IRON AND STEEL

In integrated steelworks iron ore is reduced with coke to form pig iron. This is then further reduced in blast furnaces to produce steel. CO_2 emissions result from the combustion of coke and derived gases.

In electric arc furnace (EAF) steel production, scrap is molten together with cold pig iron. The heat needed to melt the charge is provided by the energy liberated when the arcs are struck between the electrodes and the charge, although additional energy is provided by the combustion of fossil fuels. CO_2 emissions result from the combustion of these fuels and the carbon in iron.

9.1 AVAILABLE INFORMATION

Plant level data on operator, location and production capacity was available through a SteelEye survey [SteelEye, 2001]. For Norway, UK and the Netherlands national emission authorities reported actual emission data. For other countries CO_2 emission were calculated based on emission factor.

9.2 CALCULATION OF EMISSION OF CARBON DIOXIDE

For integrated steelworks the process steps of iron making and steel making were considered. Treatment of ore and raw materials were not considered here. CO_2 emissions stem from the blast furnace, having an emission factor of 1.14-14.40 kg CO_2/kg steel (mean value: 1.27 kg CO_2/kg steel).

For EAF a specific energy consumption of 4551 MJ per tonne of liquid steel was assumed, of which 89% is electricity and 11% is fossil fuel (coal, coke, carbon in iron) [IISI, 1998]. Further it was assumed that electricity was provided by the electricity grid thus resulting in zero emission at the steel site. Using an emission factor of 0.28 kg CO_2/MJ for fossil fuel combustion, results in a steel making emission factor of 0.14 kg CO_2/kg steel.

9.3 COVERAGE OF EMISSION IN THE DATABASE

940 plants are included in the database located worldwide. For 74% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.
The total steel production capacity in the database is 836 Mt and the calculated production is 745 Mt. For the year 2000, the International Iron and Steel Institute reported a world steel production of 847 Mt. The database coverage of world steel production is

88%. The omissions stem mostly from the low coverage for Japan and China, each having coverage of around 50%. This is mainly caused by lack of information on the production capacity of the individual plants (so the plant existence is known but the production capacity is taken to be zero).

10 POWER PLANTS

Emissions from power plants result from the combustion of fossil fuels. The concentration of CO_2 in the flue gas depends on the fuel type and the plant type.

Conventional coal-fired power plant produce flue gases with a CO_2 concentration of around 15%, whereas for natural gas-fired conventional stations this is 8%. When refinery gas, coke oven gas or blast furnace gas is used, the concentrations are higher, approximately 15-20%.

In gas turbines gas is burned with in excess of air, resulting in a lower CO_2 concentration of 3-4%. Gas turbines are used in combined cycle plants.

10.1 AVAILABLE INFORMATION

Plant level emission data for public power stations were reported by national environmental agencies for the Netherlands, Norway and UK. For the USA, plant level emission data were reported by the US Environmental Protection Agency Office of Atmospheric Programs, for public and commercial/industrial power stations as well.
For the rest of the world, plant location, capacity, fuel type and technology was collected from the World Electric Power Plants database [WEPP, 2001]. The WEPP database contains detailed information on all types of public and commercial/industrial power plants: fossil, nuclear, biomass, waste, solar, wind, hydro and geothermal stations. Although the WEPP database does contain smaller plants (<50 MW), the emphasis is on large-scale power plants.

10.2 CALCULATION OF EMISSION OF CARBON DIOXIDE

Except for the Netherlands, Norway, UK and USA no emissions were reported on plant level. For these countries an emission factor was used. For each country, different emission factors for coal, oil and gas were taken from the IEA Statistics study on CO_2 emissions [IEA, 2000*a*]. Capacity factors for each country and fuel type were based on production and generating capacities from the IEA study on electricity [IEA, 2000*b*].

10.3 COVERAGE OF EMISSION IN THE DATABASE

7956 plants are included in the database located worldwide. For 81% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.
The production of electricity and heat from coal, oil and gas combustion was 19 PWh in 1998 [IEA, 2000*b*]. The Ecofys inventory contains production data, except for Germany, The Netherlands and UK. For the USA year 2000 data is used. To be able to compare the

IEA figures to the Ecofys inventory, data for these countries were excluded from the IEA figures; in this case, the 1998 production was 15 PWh. In the Ecofys inventory the generation of power and heat amounts to 11 PWh for the same countries so the coverage on power production is 75%. Looking regionally, the coverage for Eastern Europe and the CIS is low (50% and 25% respectively). This may be caused by the high rate of heat generation in these countries: the reported capacity of a power plant does not in all cases reflect the thermal capacity, causing an error in the estimation of the output.

11 CEMENT PRODUCTION

Carbon dioxide is produced during cement production by calcination of raw material and by combustion of fuel. The main source of carbon dioxide is the production of clinker, the intermediate product from which cement is made. High temperature kilns are used for the calcination reaction where limestone (calcium carbonate) breaks down into clinker (calcium oxide) and CO_2. CO_2 emission from clinker amount to about 0.5 kg/kg. The specific process emission per tonne of cement depends on the ratio clinker/cement and varies normally between 0.5 and 0.95. The second source of CO_2 is from fuel combustion. Practically all fuel in the cement making process is used during pyroprocessing: fuel is burned in the rotary kiln and raw meal flows counter-current to a stream of hot gas. The amount of carbon dioxide emitted during this process is mainly influenced by the technology applied and the type of fuel used; mostly coal and natural gas, but also fuel oil, petroleum, coke and alternative fuels. On average about 55 to 60% of the direct CO_2 emissions stems from process emissions and 40 to 45% from fuel combustion. The concentration of CO_2 in the flue gas is relative high and generally between 20 and 30%, depending on fuel type and technology applied [IEA R&D, 1999].

11.1 AVAILABLE INFORMATION

Worldwide many cement companies are operational, but no cement association is active worldwide. Information on cement production, capacity, properties and fuel use on plant level is therefore scarcely available and often scattered present. An important information source identified is the World Directory on Cement published by the European Cembureau (in short WCD).[8] The latest edition available (1996) gives information on more than 2100 cement plant worldwide.[9] The database includes (amongst other) information on company name and location, clinker capacity, technologies applied, initial year of operation and type of fuel. However, the data is provided on voluntarily basis and is not complete [Cembureau, 1996].

11.2 CALCULATION OF EMISSION OF CARBON DIOXIDE

Emissions of CO_2 are not reported in the WCD. Based on available information in the database on applied technologies, fuel emission factors are estimated per plant. Table 11-1 gives an overview of the specific energy consumption for clinker production per technology and the emission factors per fuel used in the calculations.

[8] Another source with substantial information on cement facilities can be found at http://www.global-cement.dk/. The presented information, however, could not be obtained in a way that it could be electronically processed.
[9] The next edition for 2001 is expected at the end of 2001.

11.3 COVERAGE OF EMISSION IN THE DATABASE

2136 plants are included in the database located worldwide. For 77% of the plants the longitude/latitude co-ordinates could be identified. See Table 2-4 and Table 2-5 for detailed regional coverage.

The total reported capacity in the WCD is 1190 Mt of clinker.[10] In 1996 the total production is estimated at 1290 Mt of clinker [IEA R&D, 1999]. From this we can conclude that about 90% of the clinker production is reported in the database.
The emission of carbon dioxide from clinker production calculated as described in section 11.2 amounts to 936 Mt; of which 401 Mt (43%) from fuel use and 534 Mt (57%) from process emissions. These calculated emissions do not include indirect emissions from power production.
In 1996, the CO_2 emissions from cement production amounted to about 1160 Mt [IEA R&D, 1999]. Emission from power use can make up about 10% of total CO_2 emissions from cement making. Direct emissions are therefore estimated at 1044 Mt (90% of 1160 Mt). The calculated direct emissions (936 Mt) represent therefore about 90% of the 1996 reported emissions.

Table 11-1 Specific energy consumption for clinker production per technology and emission factor per fuel type.

Dry process (GJ/t)	3.6
Dry process with precalcination (GJ/t)	3.3
Semi-dry process (GJ/t)	4.0
Semi-wet process (GJ/t)	4.8
Wet process (GJ/t)	5.9
Other and not-defined processes (GJ/t)	4.0
Emission factor coal (kg/GJ)	104
Emission factor fuel oil (kg/GJ)	76
Emission factor gas (kg/GJ)	56
Emission factor petcoke (kg/GJ)	76
Emission factor hv fuel oil (kg/GJ)	86
Emission factor other fuel (kg/GJ)	86

[10] Reported is the 1996 production when available. In case 1996 data was not available the production from an earlier year has been reported.

12 FUTURE CO_2 EMISSION SOURCES

In this chapter the methodology for predicting magnitude and location of future CO_2 emission sources is presented. Section 10.1 describes how the location of new production capacity is located. Section 10.2 describes the sources and methodology used to determine the magnitude of the CO_2 emission source at each location.

12.1 FUTURE NEW CAPACITY PROJECTION

The growth in production in the industrial sectors will involve the expansion of existing plants and the construction of new plants. Factors influencing the choice for a specific location for new plants include:

- The proximity of markets for final or intermediate products
- The proximity of suppliers
- The availability of human resources (labour force)
- The availability of natural resources, e.g. ores, fuels, cooling water, land
- The availability of infrastructure, e.g. harbours, roads, railways

For industrialised countries the infrastructural and industrial developments are assumed to be so mature that new capacity will be constructed in the same areas as where production is currently located. Factors determining the choice for a location, such as mentioned above are not expected to change in these countries.

For developing countries this might be different. The factors mentioned may change, as markets are expanding into new areas. This raises the question, which of the various factors are dominant in the decision for a new location. For a steel plant, for instance, the general factors of availability of labour and the proximity of markets is complemented by the availability of iron ore, coal and scrap. Since markets, iron ore mine, coal mines and steel scrap resources are generally not located in the same place, transporting part of the resources will be necessary. Depending on the location of the steel plant, this may involve e.g.:

- transporting iron ore to a plant near a coal mine or a harbour
- transporting coal to a plant near a iron ore mine or a harbour
- transporting supplies to and products from a plant near a iron ore mine or a coal mine
- transporting iron ore and coal to a plant near the proximity of markets and labour forces

Which of the above options is the most favourable in economic and organisational respect depends on e.g. the availability and quality of roads and railway, the quality of domestic coal vs. imported coal, the distances between coal mines, iron ore mines, markets, the value of the products, etc. Combined with the uncertainties of where future markets and infrastructure will be located makes it very difficult to predict the most likely location for future production capacity.

An analysis of current locations for some specific cases (i.e. power plants in India, iron & steel plants in India and China [DOE, 2001]) also shows no clear link between the sites of coal mines, iron ore mines and the location of existing plants that can be used as a rule of thumb in the decision of where plants are constructed. From this it can be concluded that the decision to construct the already existing plants on their current location may include additional factors than mentioned above, factors on which we have no information. This makes it very difficult to forecast the future location of new plants.

The fact that in the past location-determining factors at the current sites were favourable may indicate that these factors will also be favourable for future capacity additions. Infrastructure, such as road and harbours, is already available at the current locations, while for new locations this will probably still need to be developed. Distances between human and natural resources, plant location and markets are apparently not prohibitively large for current locations and may therefore also expected to be sufficiently favourable for future capacity additions. Based on the above-mentioned we have assumed that future capacity additions will take place at the location of existing plants. This means that the additional capacity has been proportionally allocated over the current production sites.

12.2 Growth projections

Based on the database of existing emission sources, a first indication of future CO_2 emissions is provided for the years 2010 and 2020. The outlook is mainly based on the expected growth rate of individual sectors and the expected reduction of specific energy consumption. Where available, the outlook is based on growth assumptions for individual countries. In other cases, regional growth data is used to approximate data for individual countries within that region.
Methodology
The main formula used for the calculations reads:

$$E(T) = E(B) * (1 + \text{prod.growth})^{(T-B)} * (1 - \text{en.cons.})^{(T-B)}$$

With:
E(B): Emissions reported base year
E(T): Emissions year T
Prod. growth: Average annual production growth rate
En. cons.: Average annual reduction of specific energy consumption

All calculations made in the outlook are based on this formula, except for the iron and steel sector and the power sector. For the power sector, a distinction is made between production from coal, gas, oil and other fuels (mainly waste and biomass). Thus, separate estimations are made for production growth figures and estimated reduction of specific energy consumption for the four types of fuel mentioned. For the iron and steel sector the annual growth figures are corrected for the assumed increase in electric arc furnace (see description below).

12.3 Available information

The main data sources used in the outlook are:

- WEC: Efficient Use of Energy Utilizing High Technology – An Assessment of Energy Use in Industry and Buildings, World Energy Council, September 1995
- EU Outlook: European Commission, European Union Energy Outlook to 2020, Special Issue - November 1999.
- WEO 2000 International Energy Agency, World Energy Outlook 2000
- AEO 2001: US Department of Energy, Annual Energy Outlook 2001
- EIA 2001: Energy Information Agency, International Energy Outlook 2001
- IEA 2000: Energy Policies of IEA countries; 2000 review

Ammonia

The main data source used for the outlook on the ammonia industry is the World Energy Council (WEC) outlook. In this document, the ammonia production in OECD countries is assumed to stabilise; thus average annual production growth is set at 0.0%. In Eastern European and CIS countries, the average production growth is assumed to be 0.5%, whereas production in developing countries is assumed to reach an average of 4.0% annually throughout the whole period (up till 2020). Estimations on average annual reduction of specific energy consumption do not vary much throughout the world. For OECD countries an annual reduction of 1.1% is assumed; for other countries and other regions 1.2%.

Hydrogen

As very little information is available on future developments on the market of hydrogen production, own estimations had to be made. As in the inventory only hydrogen production from refineries were considered, the most likely assumption for hydrogen production growth is to assume this to be equal to production growth rates of production from refineries. This ranges from 0.7 in Japan to 5.1% in the Chinese region in the year 2010 and from 0.8% in Canada and OECD Europe to 4.3% in the Chinese region in the year 2020. In some regions, it could be expected that higher environmental standards and quality requirements for refined products could result in higher growth factors for hydrogen production, but too little quantitative information is available to be taken into account. Average annual reduction of specific energy consumption in hydrogen production is assumed to be equal to the generally assumed autonomous annual production growth in industry, i.e. -1.0%.

Ethylene

Production growth data for ethylene production were based on the outlook published by the Saudi Basic Industries Corporation [SABIC, 2001]. Their outlook up till the year 2009 provides average annual production growth data on a regional basis, as well as detailed outlooks for the Saudi region on a country basis (from 0% in Iraq and the United Arabic Emirates up to 16% for Iran). Regional growth rates for other regions and outlooks beyond 2010 are taken from WEC. The rates vary between 0.0 and 5.0%.

Average annual reduction of specific energy consumption is taken from WEC, ranging from 0.5% in OECD countries to 1.3% for Eastern European and CIS countries.

Ethylene oxide

The overall growth in demand for ethylene oxide is assumed to grow with demand for ethylene glycol. According to recent estimations from BASF, productions in the period 2000-2010 in OECD countries are expected to increase by 5.0% [BASF, 2001]. Annual production growth rates for development countries are set at 3.6%. Average annual reduction of specific energy consumption is set at similar rates as for ethylene production: from 0.5% in OECD countries to 1.3% for Eastern European and CIS countries.

Oil and gas processing

For the outlook on future production growth in oil and gas processing different sources were available. The EU energy outlook provides average annual production growth rates for the individual EU Member States. The AEO 2001 was used for the outlook for the USA. Future estimates on other regions were taken from WEO 2000, ranging from –0.3% for Eastern European and CIS countries to 2.25% to Middle East and Africa. As the inventory concentrates only on the process-related emissions - which is separated from the natural gas - energy related CO_2 emissions are not included. Therefore, changes in the average annual reduction of specific energy consumption do not have to be included in the calculations.

Refineries

Production growth estimates are constructed in a similar way as conducted in the WEC outlook: derived from oil consumption forecasts by country or region. In this, the production of refined products is expected to keep pace with oil demand. The actual data used for the outlook were taken from recent calculations in the EIA 2001. In addition, the EU outlook was used for the outlook on individual EU countries. Average annual production growth rates vary between 0.7% in Japan to 5.1% in the Chinese region in the year 2010 and from 0.8% in Canada and OECD Europe to 4.3% in the Chinese region in the year 2020. The average annual reduction of specific energy consumption are directly taken from the WEC, ranging between –0.5% in OECD countries to –0.7% in developing countries (data for both periods). For developing countries and the Eastern European and CIS region, it is assumed that refining becomes more complex as the demand for light-end distillates increases.

Iron and steel

The production growth data for the iron and steel sector is mainly taken from projections of IISI in the Delphi study [IISI, 2001]. In addition, detailed production growth data for EU countries were taken from the EU energy outlook (from –0.3/-0.8% in Denmark to 2.6/1.0% in Finland, in the year 2010 or 2020 respectively). The average annual reduction of specific energy consumption is directly taken from the WEC. For an accurate estimation of future CO_2 emissions, a third factor should be taken into account next to the overall production growth rate and the reduction of specific energy consumption, being the increased share of the Electric Arc Furnace (EAF) in liquid steel production. This information is provided by IISI in the Delphi study. The average world-wide share of EAF is expected to increase from 33% in 1999 to 40% in 2010. The calculations for future emissions take into account estimations on a country level.

Power

The inventory on the power sector concentrates on the fossil-fuelled electricity production. As was mentioned in the previous section, a distinction is made between production from coal, gas, oil and other fuels (mainly waste and biomass). Production growth data for the EU countries are taken from the EU energy outlook. For other countries and regions detailed data is obtained from WEO 2000, IEA 2000 and EIA 2001. The average annual reductions of specific energy consumption are based on own estimations.

Cement

In January 1999, a report was published for the IEA Greenhouse Gas R&D Programme on the greenhouse gases from cement production [IEA R&D, 1999]. The projections on production growth on a regional basis are directly taken from this study. Data ranges from 0.0% in OECD Europe to 4.0% in 2010 and 4.5% in 2020 for the Chinese region. Average annual reduction of specific energy consumption is taken from WEC, ranging from 0.6% in OECD countries to 0.8% in developing countries.

Summary and conclusions

Table 12-1 summarises the data used for the outlook on emissions in 2010 and 2020. As mentioned before, data is included in the database on a country level where available and on a regional level otherwise. Table 12-3 and Table 12-4 shows the estimated CO_2 emission per industry for each region.

Table 12-1 Data used for outlook on emissions in 2010 and 2020

	Regional range of production growth 2010		Regional range of production growth 2020		Regional range of average annual change of specific energy consumption	
	[average ann. growth rate]		[average annual growth rate]		[average annual growth rate]	
	Min	Max	Min	Max	Min	Max
Ammonia	0.0	4.0	0.0	4.0	-1.1	-1.2
Hydrogen	0.7	5.1	0.75	4.3	-1.0	-1.0
Ethylene	0.0	5.0	0.0	5.0	-0.5	-1.3
Ethylene Oxide	3.6	5.0	3.6	5.0	-0.5	-1.3
Oil&Gas Processing	0.0	2.3	-2.3	2.3	0.0	0.0
Refineries	0.7	5.1	0.75	4.3	-0.5	-0.7
Iron&Steel	0.1	6.0	0.1	6.0	-0.5	-0.9
Power	-0.8	5.6	-0.8	5.3	0.0	-1.4
Cement	0.0	4.0	0.0	4.5	-0.6	-0.8

The emissions are projected to grow by 36% in 2010 and by 73% in 2020. The grow is modest for the iron and steel sector (13% in 2020), because of the foreseen shift in production technology. Limited growth in emissions is also projected for ammonia, gas processing and cement production (31%), with the highest growth rates in developing countries. High growth are projected for power (81%) and ethylene oxide (114%), the latter with high growth rates especially in developed countries.

Table 12-2 Estimated emissions in 2000.

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processing	Hydrogen	Iron & steel	Power	Refineries	Total
	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Tg CO2
Africa	3612	58173	3493		0	217	13726	355629	32262	**467**
Canada	1409	11492	11473	273	8873	1812	14468	171409	18656	**240**
China Region	34128	57362	22296	705	0	430	77683	3016328	51334	**3260**
CIS (including Baltic states)	12752	77294	11390		10	582	92043	719603	98306	**1012**
East Asia	2070	119996	21248	423	45220	1816	21724	494296	59730	**767**
Eastern Europe	4408	43213	6981		327	197	34043	466929	19326	**575**
India Region	3517	75844	10092	214	0	410	29635	551521	32743	**704**
Japan	1534	77091	11242	360		4101	70652	656453	48143	**870**
Latin America	7662	112524	20155	263	4471	2226	42007	266043	81216	**537**
Middle East	2537	81935	28617	509	0	3905	15555	384791	65420	**583**
North America (rest)								770		**1**
Oceania	822	8244	1148		2496	202	13518	234581	9359	**270**
OECD Europe	14606	149348	50429	1211	3157	6163	142258	1211389	128009	**1707**
USA	7397	62921	60896	1495	0	8724	83361	2063171	159918	**2448**
Total	**96454**	**935436**	**259458**	**5454**	**64553**	**30786**	**650673**	**10592913**	**804423**	**13440**

Table 12-3 Estimated emissions in 2010.

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processing	Hydrogen	Iron & steel	Power	Refineries	Total
	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Tg CO2
Africa	4739	54041	5086		0	265	13446	458028	43626	**579**
Canada	1261	12142	13926	427	7598	1952	14413	171692	22431	**246**
China Region	44772	88509	31080	945	0	665	102259	5387440	88222	**5744**
CIS (including Baltic states)	11880	98257	12089		9	615	84532	775788	115958	**1099**
East Asia	2715	157244	30695	574	54797	2442	28520	742388	89694	**1109**
Eastern Europe	4107	54933	7400		317	233	31086	583138	23751	**705**
India Region	4614	99180	14240	293	0	553	46140	900576	47154	**1113**
Japan	2033	89619	10458	486		3976	70625	593443	52136	**823**
Latin America	10052	122194	25948	358	5484	2980	41263	382300	119070	**710**
Middle East	2248	84232	35710	696	0	4742	14768	577413	91100	**811**
North America (rest)								1020		**1**
Oceania	736	8711	1276		2496	210	18128	248454	10868	**291**
OECD Europe	13077	137281	52686	1964	1902	7142	140224	1487140	142870	**1984**
USA	6622	66482	73854	2341	0	9216	82887	2597043	188666	**3027**
Total	**108857**	**1072824**	**314447**	**8084**	**72605**	**34991**	**688292**	**14905864**	**1035547**	**18242**

Table 12-4 Estimated emissions in 2020.

Region (EDGAR)	Ammonia	Cement	Ethylene	Ethylene oxide	Gas processing	Hydrogen	Iron & steel	Power	Refineries	Total
	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Gg CO2	Tg CO2
Africa	6217	60767	7723		0	311	13411	569714	56362	**715**
Canada	1129	11433	17271	642	6507	1903	14629	172546	24179	**250**
China Region	58737	126367	47192	1255	0	915	140637	8179920	134168	**8689**
CIS (including Baltic states)	11067	111182	12929		9	669	77896	868448	139449	**1222**
East Asia	3562	198514	46607	762	66403	2925	39199	1134756	118776	**1612**
Eastern Europe	3826	62159	7914		308	217	28629	698867	28194	**830**
India Region	6053	125254	21622	389	0	709	76710	1290595	66887	**1588**
Japan	2695	96382	9651	639		3978	71738	531299	57682	**774**
Latin America	13187	139360	35804	475	6728	4015	41167	505777	174864	**921**
Middle East	1993	91529	54221	924	0	5393	14679	786435	125357	**1081**
North America (rest)								1323		**1**
Oceania	659	8202	1436		2496	214	25484	271021	12227	**322**
OECD Europe	11707	129263	55353	3042	1571	6997	109696	1737430	147526	**2203**
USA	5929	62599	91593	3519	0	9277	84093	2637506	209997	**3105**
Total	**126761**	**1223011**	**409314**	**11647**	**84021**	**37523**	**737967**	**19385638**	**1295667**	**23312**

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13 CONCLUSIONS

This study inventory the carbon dioxide emission of large industrial sources, namely fossil-fuel fired power plants, chemical plants (ammonia, ethylene and ethylene oxide), refineries, iron and steel plants, cement plants, power plants and natural gas processing sites. The constructed database contains information by plant, including plant name, company name, location (city, country, region), latitude and longitude co-ordinates of the plant, yearly CO_2 emission of base year and projected emissions in 2010 and 2020 following growth rates on country or region level.

Data on emission of CO_2 on plant level are scarcely available and often confidential or not published in a systematic way. Therefore, the database provides next to reported emissions also calculated emission estimates based on production figures or on capacity figures. The emission factors are based on information on technology and fuel used.

Although we tried to be as accurate as possible, the information contained in the database has its limitations. Partly this can be improved in possible future updates, partly it is inherent with the set-up and approach of the database.

Not in all cases the technology applied and fuel used are known. Emissions of CO_2 are, however, depending on these aspects. In estimating the emissions, and by absence of information on technology and/or fuel use, the most common used are assumed.

For ammonia production there was no information available on technology used. Especially in recent years, technology is implemented resulting in off-gases with lower CO_2 concentrations. Hydrogen production is often integrated in refinery activities. In gas processing, data on CO_2 content in the produced gas is regarded to be confidentially and is therefore not publicly available. However, improvement in quality of data on CO_2 content will be required to identify sources of pure CO_2 in gas processing with more confidence.

The emission data are sometimes based on production in one year, instead of capacity. In some cases this might lead to an underestimation of emissions, because the particular plant might not have been operating as in usual years.

Finally, little information is incorporated in the database on new plants. This information is only scarcely available and often not on a systematically way accessible.

14 REFERENCES

AEA Technology, 1999. *The reduction of greenhouse gas emissions from the oil refining and petrochemical industry*. IEA Greenhouse Gas R&D Programme, June 1999.

AEO, 2001. *Annual Energy Outlook 2001*, US Department of Energy, Washington D.C.

BASF, 2001. *Adding value through growth and innovation; Petrochemicals; the road ahead*, presentation by Dr. J. Hambrecht, BASF Steam Cracker Day, Port Arthur, Texas, June 11-12 2001.

BAT, 1997. *Best Available Technique Reference Document on Ammonia Production*, Commission of the European Communities, C. Hendriks and D.Papameletiou, Institute for Prospective Technological Studies (IPTS), Seville, Spain, March 1997.

Cembureau, 1996. *World Cement Directory 1996 (full version),* Cembureau, Brussels, Belgium.

ChemExpo, 2000. http://www.chemexpo.com.

ChemWeek, 2001. http://www.chemweek.com.

DOE, 2001. *Country Brief India, China*, US Department of Energy web site: www.doe.gov, 6 September 2001.

EIA, 2001. *International Energy Outlook 2001,* Energy Information Agency, Washington D.C.

European Commission, 1999. *European Union Energy Outlook to 2020*, Special Issue, European Commission, Brussels.

Foster Wheeler Review, 2001. *Revamping can increase hydrogen plant output,* JD Fleshman, NPRA Annual Meeting, New Orleans, March 2001.

GNIS, 2001. *Geographic Names Information System (GNIS)* maintained by US Geological Survey (USGS), http://geonames.usgs.gov

GNS, 2001. *Geonet Names Server (GNS)* maintained by National Imagery and Mapping Agency (NIMA), http://www.nima.mil (worldwide coverage except USA).

IEA R&D, 1999. *Greenhouse Gases from Cement Production*, Hendriks, C.A., E. Worrell, L. Price, N. Martin, L. Azawa Meida, Ecofys, LBNL, in commission of the IEA Greenhouse Gas R&D Programme.

IEA, 2000 *a*. *CO_2 emissions from fuel combustion. 2000 Edition*.

IEA, 2000 *b*. *1998 Electricity Information. 2000 Review*.

IEA, 2000. *Energy Policies of IEA countries; 2000 review*, International Energy Agency, Paris.

IISI, 1998. *Energy Use in the Steel Industry*, International Iron and Steel Institute, Brussels.

IISI, 2001. *World Steel On-line Delphi study*, International Iron & Steel Institute web site, http://www.worldsteel.org/steelmaking/techno/EAF/techno_delphi.html, 1 September 2001.

IPCC, 2000. *Draft Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry*.

Oil & Gas Journal Ethylene, 2001. *Ethylene Report*. Oil & Gas Journal / April. 23, 2001.

Oil & Gas Journal, 1999. *1999 Worldwide Refining Survey*. Oil & gas Journal / Dec. 20, 1999.

Oil & Gas Journal, 2001. *Worldwide Construction*. Oil & gas Journal / Apr. 16, 2001.

Sabic, 2001. *World Petrochemical Review, the Saudi Basic Industries Corporation,* web site: http:\\quality.anet.net.sa/en/press/press_speech_06.htm, 6 September 2001.

SRI consulting, 2000. *China Report: Chemical Product Trends*.

SteelEye, 2001. *World Steelworks Survey*.

WEC, 1995. *Efficient Use of Energy Utilizing High Technology – An Assessment of Energy Use in Industry and Buildings*, World Energy Council, London.

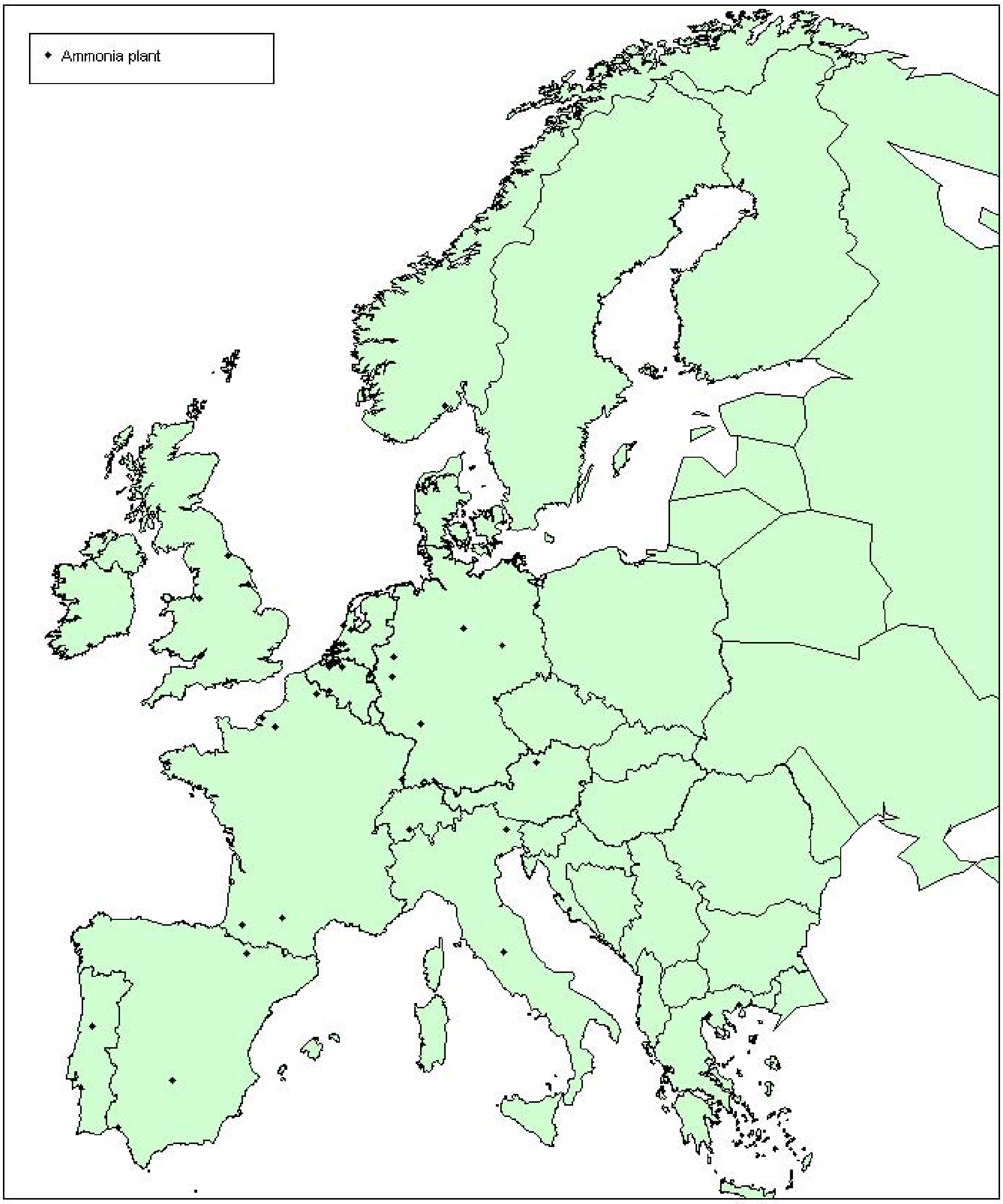
WEO, 2000. *World Energy Outlook 2000*, International Energy Agency, Paris.

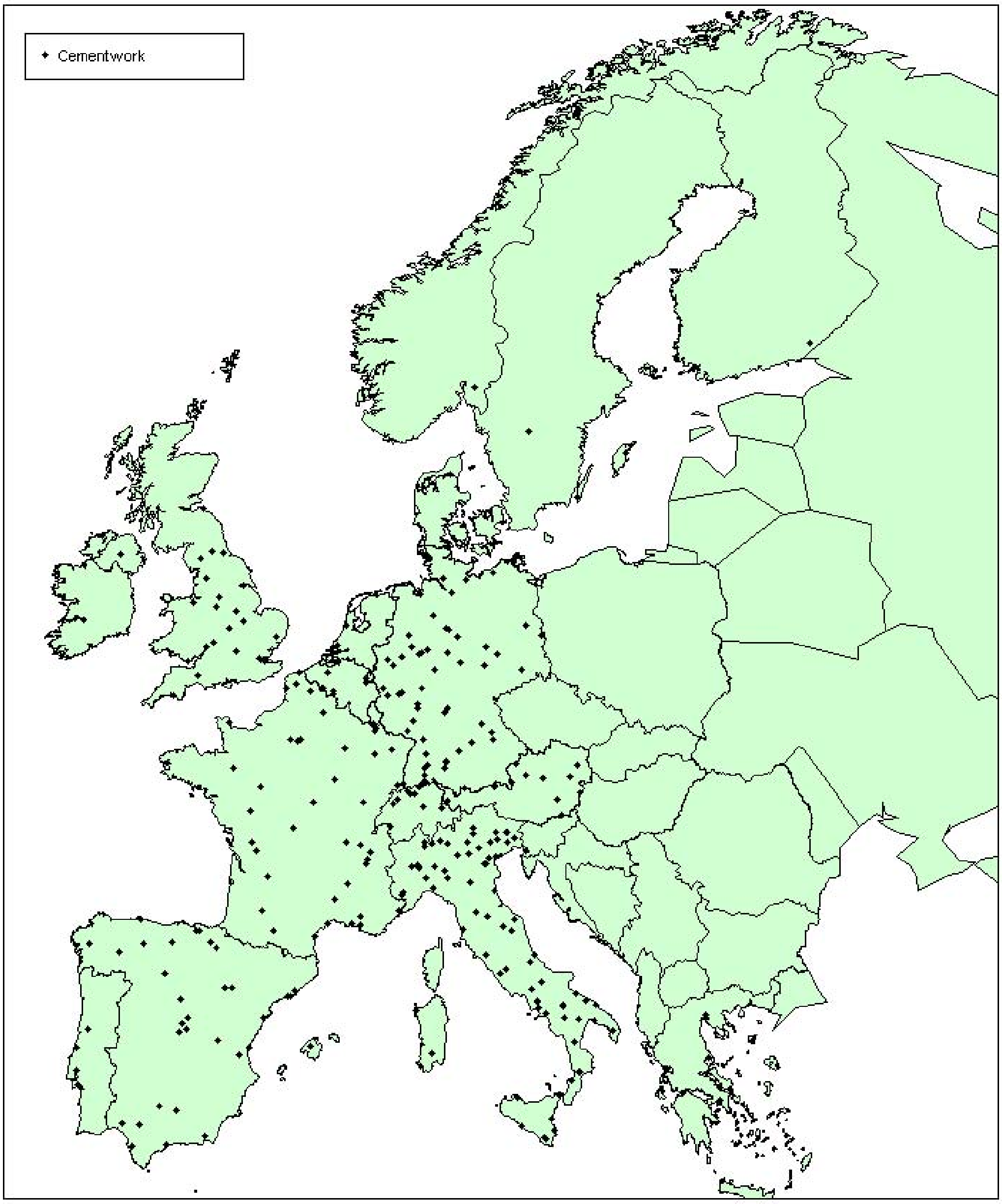
WEPP, 2001. *World Electric Power Plants database*. Platts/Mc Graw Hill.

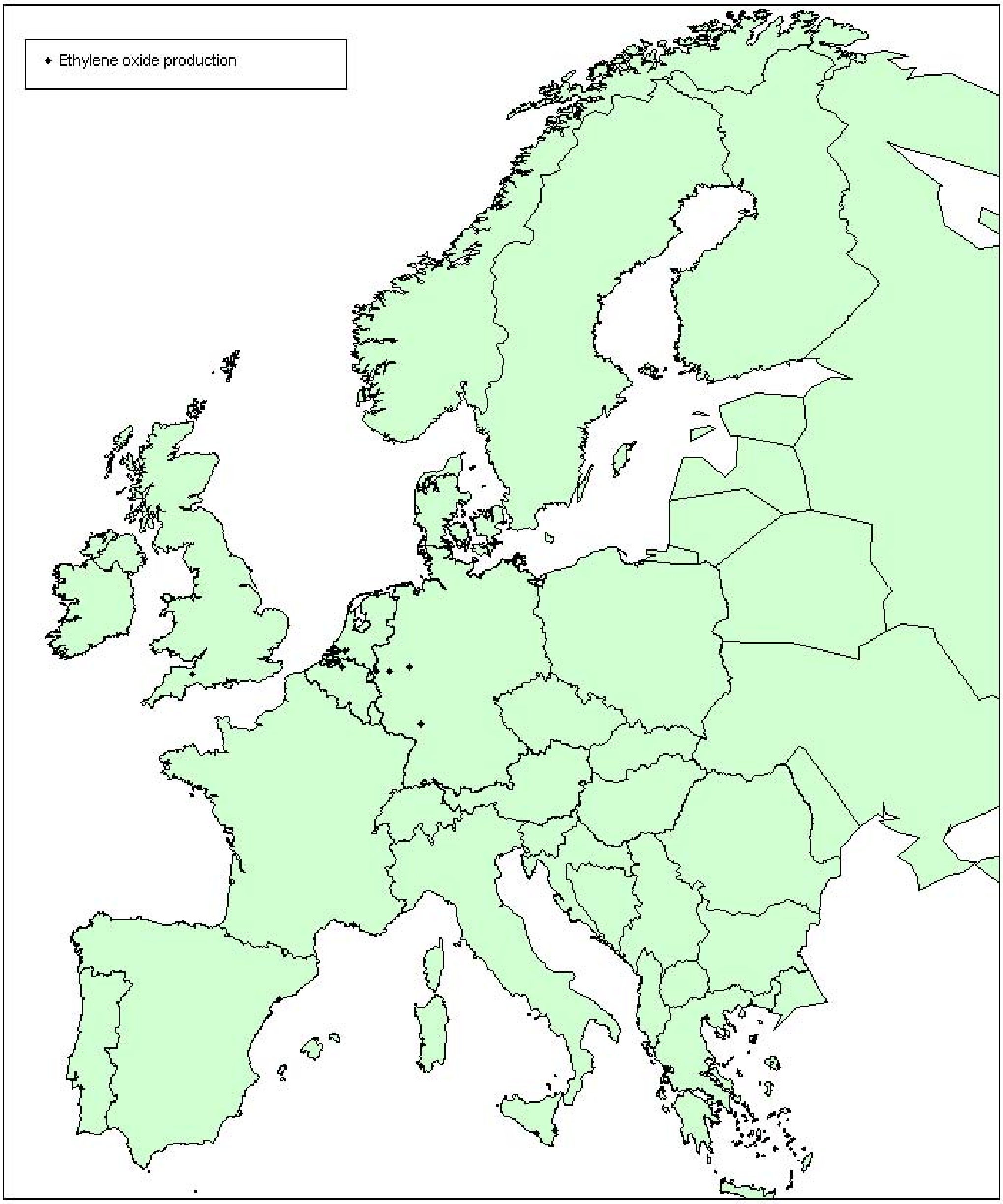
World Energy Council, 1995. *Survey of energy resources*. WEC.

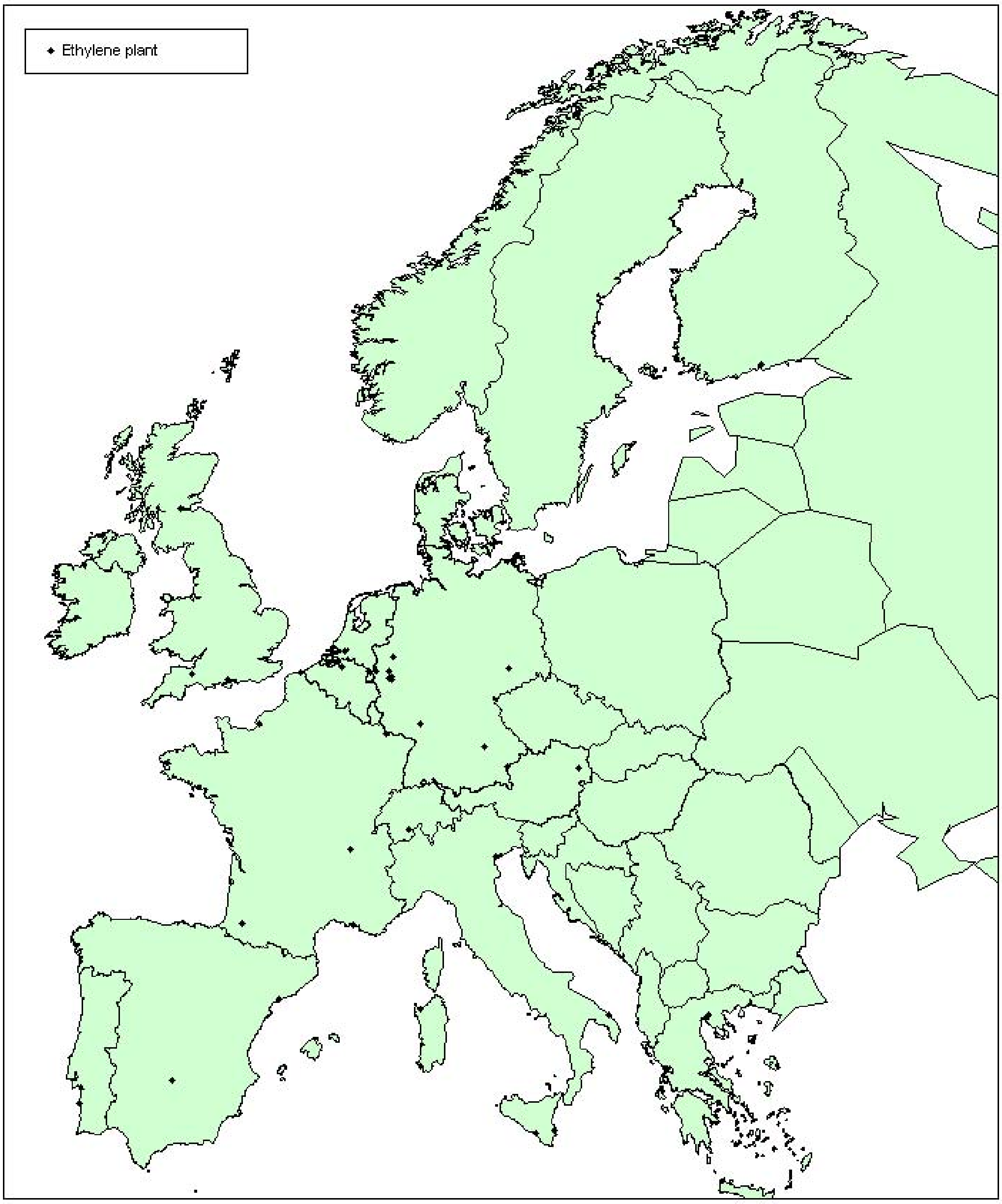
ANNEX 1

Graphical representations of industrial point sources


Ammonia plant


Cementwork


Ethylene oxide production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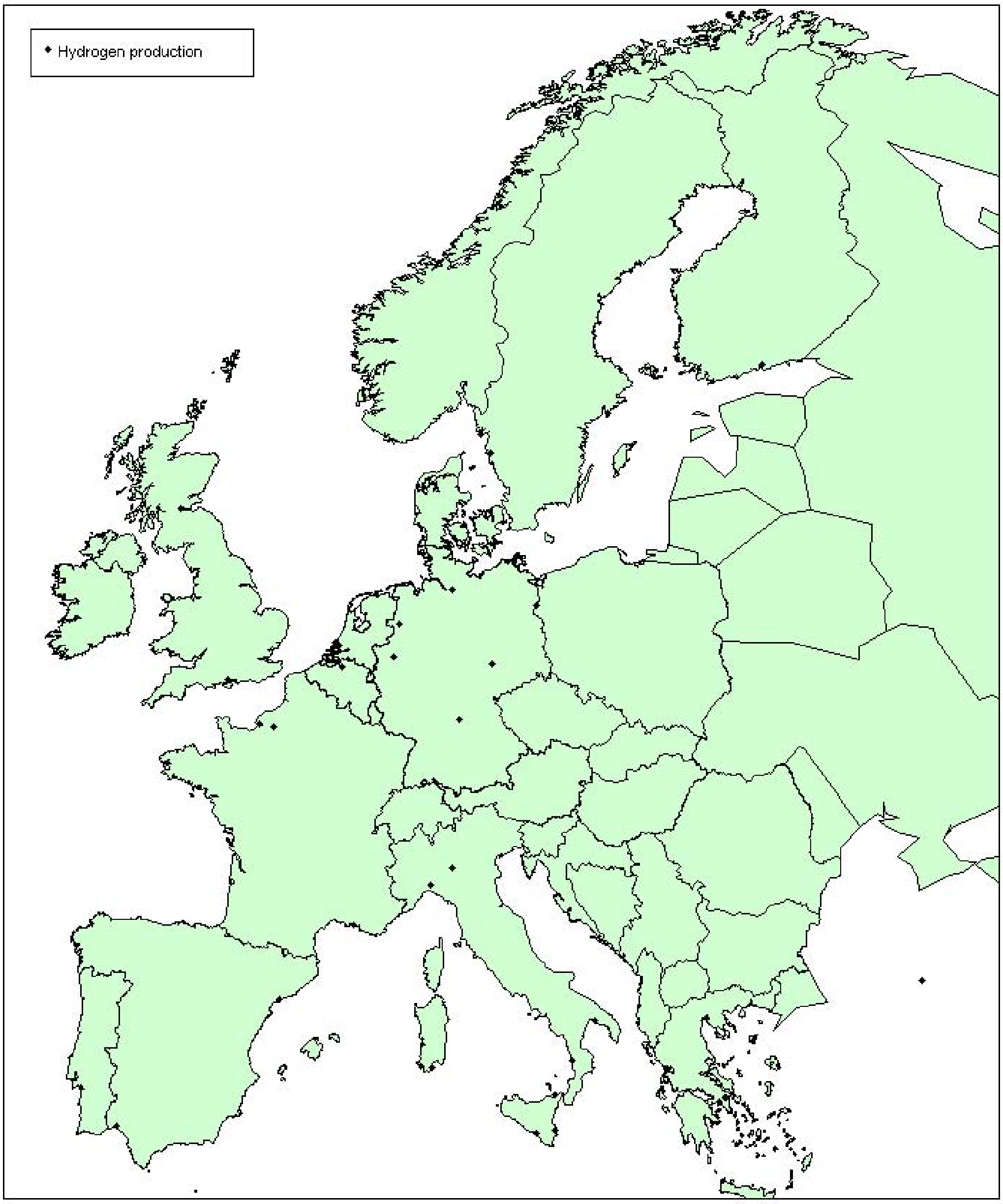
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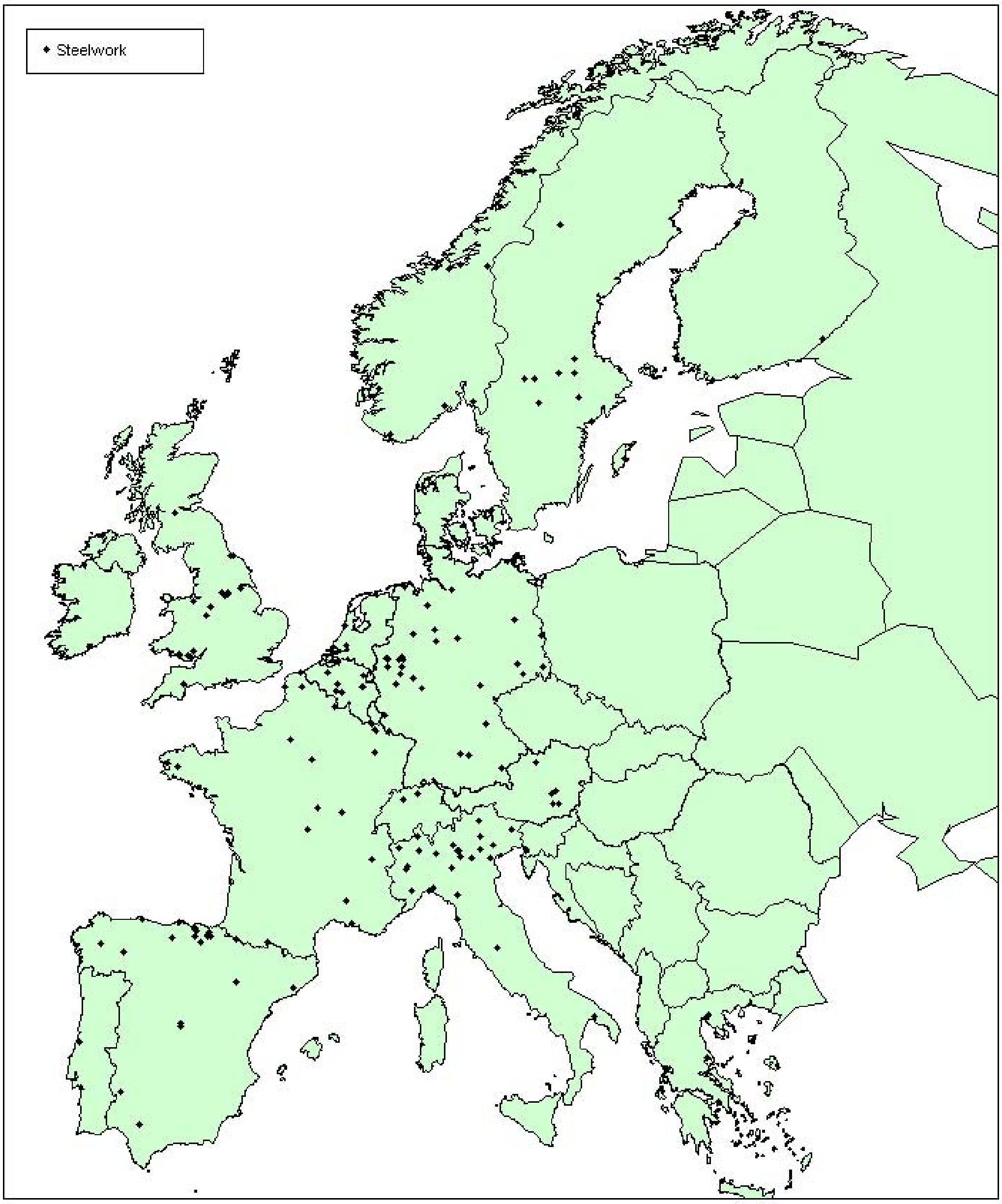
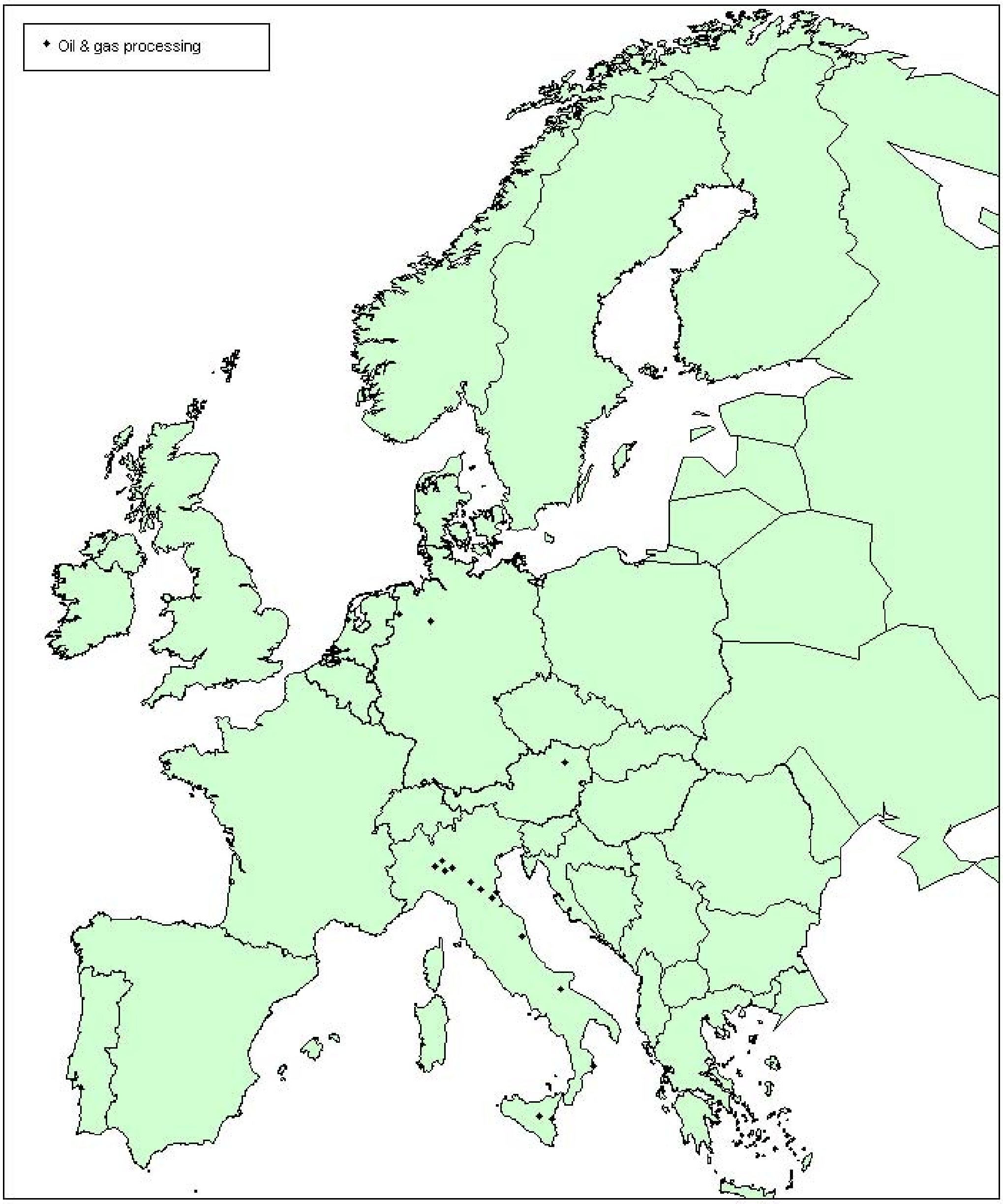
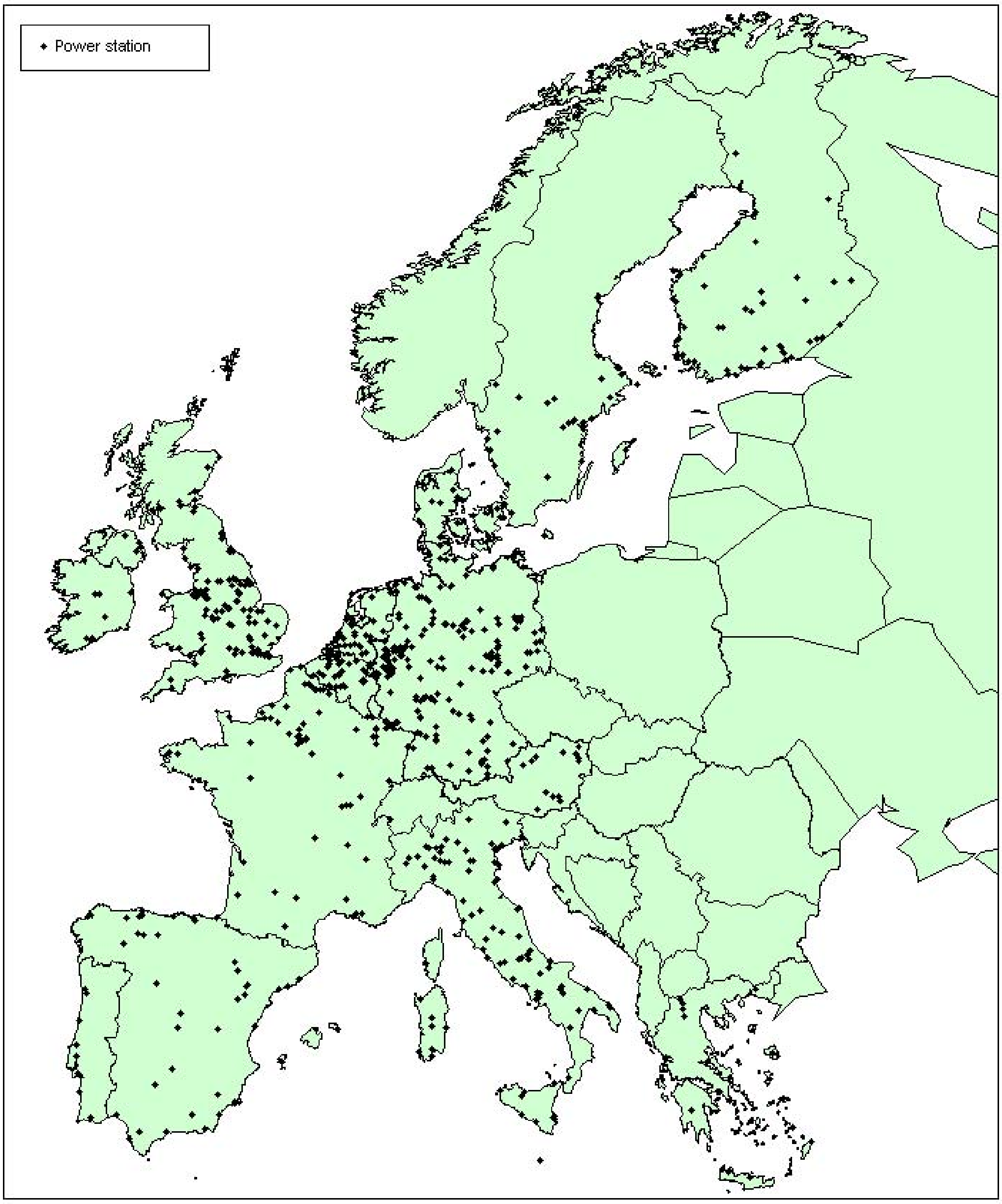
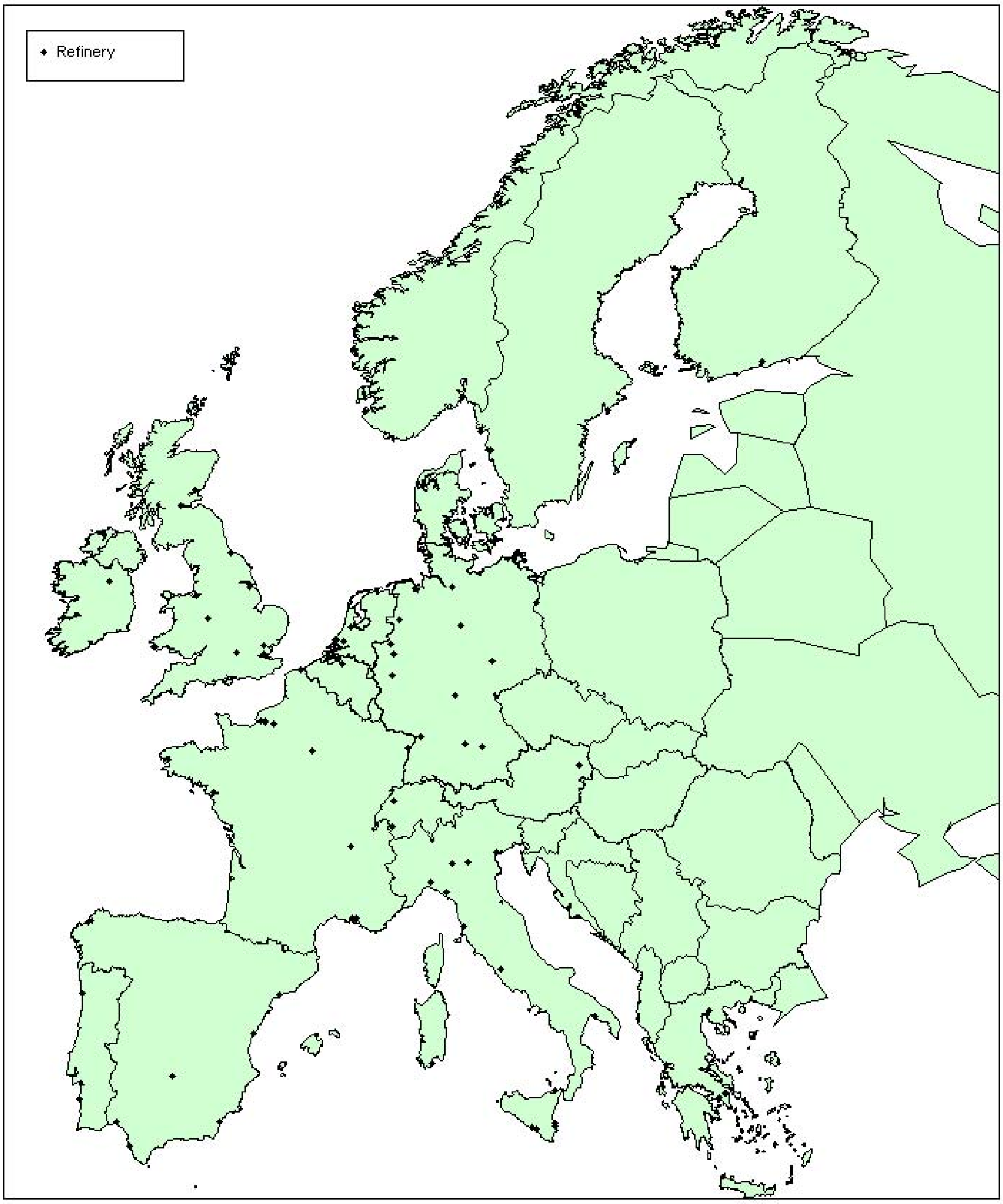

Steelwork


Oil & gas processing


Power station


Refinery

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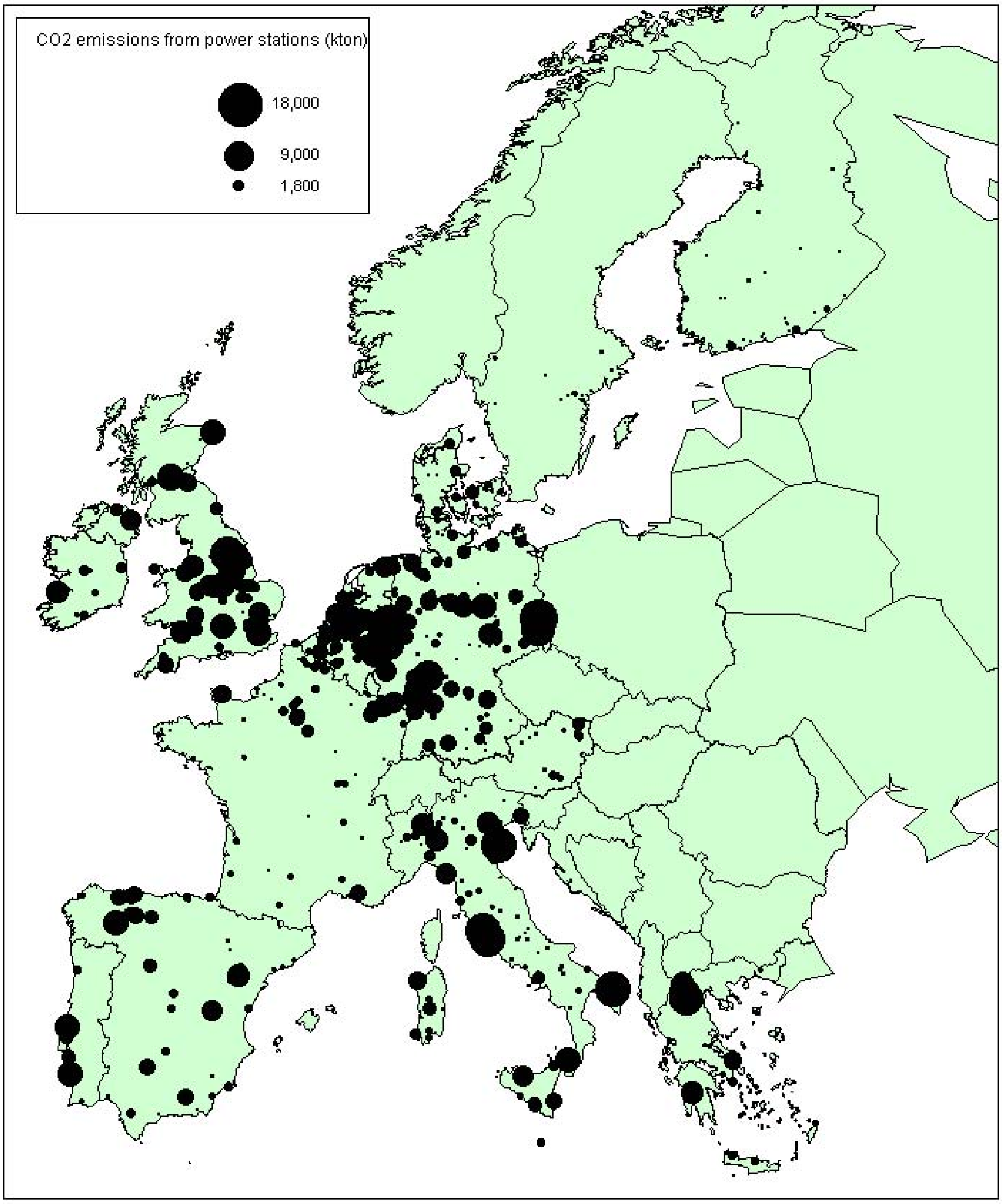

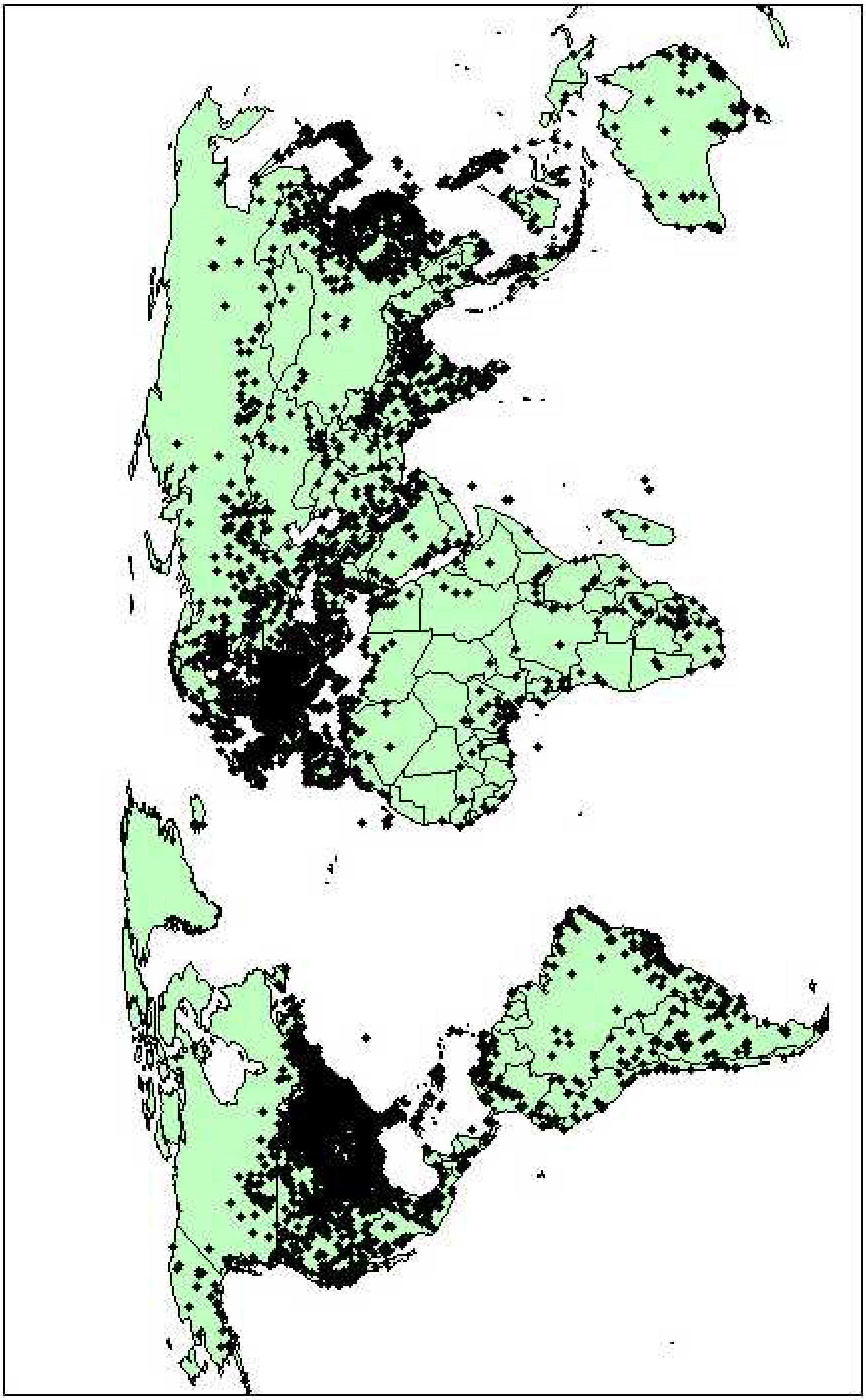

All industrial emission sources worldwide