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Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks

Energy and Transport Scenarios

Ministry of Environment and Energy, Denmark
Danish Environmental Protection Agency

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Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks

Energy and Transport Scenarios
Technical Report 7

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Contents

1 Introduction

The study

This report is part of a series of 8 reports from a life cycle assessment (LCA) comparing the potential environmental impacts associated with different packaging systems for beer and carbonated soft drinks filled and sold in Denmark.

Main report

Main report: Goal and scope definition, including description and discussions on methodology. Summary of the LCA of the different packaging systems. Comparisons of the different packaging systems. Comparison of the previous and the updated study.

Individual systems

Technical report 1: Refillable glass bottles: including description of the system, data, inventory analysis, impact assessment, and interpretation.

Technical report 2: Disposable glass bottles: including description of the system, data, inventory analysis, impact assessment, and interpretation.

Technical report 3: Aluminium cans: including description of the system, data, inventory analysis, impact assessment, and interpretation.

Technical report 4: Steel cans: including description of the system, data, inventory analysis, impact assessment, and interpretation.

Technical report 5: Refillable PET bottles: including description of the system, data, inventory analysis, impact assessment, and interpretation.

Technical report 6: Disposable PET bottles: including description of the system, data, inventory analysis, impact assessment, and interpretation.

Energy and transports

Technical report 7: Energy and transport scenarios, including energy and transport data, sensitivity analysis and data quality assessment.

Commissioner and practitioner

The study was financed by the Danish Environmental Protection Agency (DEPA). It was performed by Chalmers Industriteknik (CIT), Göteborg, Sweden and Institute for Product Development (IPU), Lyngby, Denmark.

Critical review

This report has been peer reviewed following the procedure outlined in the Main report, section 2.15.

Project framework

This report was produced during the time period from December 1997 to March 1998. The entire project was scheduled for May 1997 to March 1998.

Adherence to ISO

We adhere to the requirements of the standards ISO 14040 and ISO 14041. Several of the requirements and recommendations presented in the ISO documents need to be interpreted. We present our interpretations where applicable.

2 Fuel extraction and refining

2.1 Coal, average for Europe

The new version of the ETH data (Frischknecht *et al.* 1996) did not allow us to compute separate extraction data for hard coal from open mines, hard coal from closed (underground) mines and lignite. Since only negligible differences were found between data in Frischknecht et al. (1996) and the data in the previous version, we therefore base our calculations on the previous version (Frischknecht *et al.* 1994). Data are reported in annex A.

Emissions

Except for methane, the emissions to air for coal extraction comes from energy use. The methane emission is well documented and comes from underground mines. The water emission is caused by impurities and trace elements in raw coal and is ascribed the use of process water in mining and preparation of the raw coal. The water emission depends on the origin of the coal and the heavy metal emissions seem very uncertain. Sr (strontium) is for example a hazardous emission for which Frischknecht *et al.* use a single reference made by U.S. Department of Energy in 1980.

2.2 Oil, average for Europe

Data for the extraction and refining of heavy fuel oil, ship fuel oil, gasoil (diesel, ship diesel and light fuel oil) and LPG are taken from Frischknecht *et al.* (1994). The data cover exploration, extraction, refining and transport to stock. The data are reported in annex A.

2.3 Natural gas, North Sea

Several sources of data were compared: Boustead (1993), Frischknecht *et al.* (1994), and Bakkane (1994). The Bakkane study, which report the lowest emissions and is based on the most recent data, is chosen as the most representative source for this study. The data are reported in annex A.

2.4 Other fuels

The environmental load for the extraction of peat and bark is not included in the study. Since these fuels are used in very small amounts this would not affect the LCA results.

3 Electrical energy

3.1 Electricity scenarios

Main electricity scenario
Coal condensing

The main electricity scenario for this project is the long-term base-load marginal for the EU. This is determined in view of the planned de-regulation of the European electricity markets, which is assumed to be integrated in the current capital investment. This implies - given adequate transmission capacities - that the marginal technology is the same all over Western Europe (EU). In view of the current production costs and the constraints on the different technologies, the long-term base load marginal for a de-regulated electricity market in EU can be determined as a coal condensing power plant. This is further substantiated in section 3.2.

Fragmented markets

As part of the sensitivity analyses another electricity scenario will be used. This scenario was suggested by the international panel set up by this project to assist in selecting the correct electricity scenario. The panel concluded that: "The electricity markets in Europe are still relatively protected, fragmented markets, which makes it necessary to determine the actual marginal in each specific market (determined by country or production company). This should be done empirically as part of the project. It is not possible in advance to estimate if the result will be that the same technology is marginal in all markets." In section 3.2, it is substantiated that the EU contains 3 electricity markets, each with their long-term electricity marginal:

- One market, mainly in South and Central Europe, in which the marginal is coal condensing power, as in the main electricity scenario.
- One market, in Greece, in which the marginal electricity source is lignite.
- One market, mainly in North Europe, in which the marginal electricity source is natural gas.

Natural gas

For the sensitivity analyses, a third electricity scenario is constructed where the electricity is based on natural gas only. The purpose of this scenario is to assess the importance of our conclusions regarding what is the long-term base-load technology for electricity production.

Average electricity

As part of the sensitivity analyses, yet another scenario will be used, where all packaging systems are assumed to use an average of the EU electricity production in 1994. This scenario allows more easy comparison to the results of other life cycle assessments performed for other purposes, such as e.g. EU eco-labelling, where average electricity is typically used as a standard scenario.

Why not site-specific?

Some members of the hearing group for this project (Miljöbalans Gustav Sundström AB and the European Aluminium Association) have suggested that site-specific electricity should be applied, especially for the aluminium industry, which is often placed adjacent to sources of hydropower because of its high electricity requirement. However, the fact that an industry is situated close to a specific power source, or even owns a specific power plant, does not imply that an increased production from this industry will necessarily lead to increased output from this specific power source. Any power plant operating on market conditions delivers to the general grid as long as this is profitable. The necessary transmission capacity will be adjusted according to long term expectations in demand. The power plants with the lowest production costs, to which hydropower plants certainly belong, are utilised to their maximum capacity, disregarding any changes in the general demand. Thus, changes in the volume of aluminium production (or any other electricity consuming production) will not be able to affect the output from hydropower plants. Since hydropower is both a profitable investment and a constrained resource, its use by the aluminium industry will simply imply that another investor will not be able to make this investment. Ultimately, any change in demand affects the marginal power-producing technology (as determined in section 3.2). A site-specific power source will only be affected by a local change in demand if it is not operating on market conditions and is not linked to the general electricity market. We have not seen any evidence that the hydropower plants controlled by the aluminium industry fulfil these conditions.

3.2 Marginal electricity production

The long-term marginal electricity production technology, *i.e.* the technology installed or dismantled due to long-term changes in production volume, may differ from region to region as defined by:

- General trends in demand (see section 3.2.1)
- Production constraints (see section 3.2.2)
- Production costs (see section 3.2.3)

3.2.1 General trends in demand

The production volume of electricity has been generally increasing for the last decade both in the EU and in each national/regional submarket (Eurostat 1997b, OECD 1997). Forecasts of the electricity demand do not suggest any decrease in the coming years, neither in the EU, nor in any of the submarkets (European Commission 1996). When the production volume is generally increasing (or decreasing less than the average replacement rate for the capital equipment), the marginal technology will be the unconstrained technology with the lowest production costs.

3.2.2 Production constraints

Large scale electricity production technologies are based on nuclear, hydro, coal, oil, natural gas, biomass, waste and wind power, either as "pure" electricity production or in co-generation with heat. Many of these technologies are currently constrained, i.e. their production capacity cannot be expanded to the extent desired, due to natural capacity constraints (e.g. the amount of water available for hydro-power), political constraints (e.g. nuclear power, CO_2- or SO_2-limits), or the lack of a market for co-products (e.g. co-generated heat):

Nuclear power

For nuclear power plants it is not likely that new plants will be build within 10-15 years (European Commission 1995, 1996 & 1997). Some countries, e.g. Sweden, even plan a reduction.

Hydro power

Hydro power is limited by the areas available for establishing new plants (European Commission 1997), which may be regarded as a combination of political constraints and natural resource constraints.

Fossil fuels

Fossil fuels (coal, oil and natural gas) are not generally constrained, but may be constrained in individual countries by the emission quotas, especially the SO_2, NO_X and CO_2 targets. This implies that the most polluting technologies in these respects (i.e. especially lignite combustion but also hard coal and oil) may be constrained by these quotas. Lignite may furthermore be constrained by the EU policies for environmentally sound and sustainable energy (European Commission 1995). No development programs seem to support lignite, as is the case for renewable and other fuels (European Commission 1995 & 1997).

Biomass

Biomass as an energy source may still expand its market share, but will eventually become limited by the availability of suitable land areas (in competition with other uses of agricultural land).

Waste

Waste as an energy source is limited by the availability of the resource (waste).

Wind power

Wind power is currently expanding its market share, but the development is still constrained by the availability of technical knowledge. When this constraint is overcome, there is a fairly large expansion potential before new constraints are met due to the limited storage capacity of the intermittent wind source (which does not allow wind to be the only source for electricity generation) and due to the limited availability of areas where wind turbines are accepted for aesthetic reasons.

Co-generation

Co-generation of electricity and heat is constrained by the availability of a market for the co-product (heat).

Thus, only fossil fuels (and for a period maybe biomass and wind) have the potential to be the marginal electricity source, since they fulfil the condition of being generally unconstrained in production volume. However, country specific constraints due to emission quotas may influence *which* fossil fuel is the marginal for each submarket. In most of EU, lignite based power plants are no longer built. An exception may be Greece, where lignite power plants produce most of the electricity supply without indication of decline (Eurostat [illegible]). In the Nordic countries, the emission quotas do not leave room for much expansion of coal based power plants. At present, new power plants built are natural gas fired (Nordel 1996).

3.2.3 Production costs

Data sources and verification

The production costs are composed of operation and maintenance costs, fuel costs and depreciation and interest on capital goods (see table 3.1). Operation and maintenance costs and capital goods are taken from Energistyrelsen (1995) and data on fuel costs are given by Larsen (1997). An interest rate of 6% has been used. The calculations are made for proven technologies, relevant for new plants. The results are verified with data published by Hammar (1997). The price and maintenance of the wind turbine is verified by wind turbine manufactures. Calculations have been made for such technologies only, which may have a potential to be the marginal electricity source following the considerations in the above sections.

Assumptions on capacity utilisation

Due to fluctuation in demand, power plants operate on average at less than full capacity - in Denmark at present 40-45% of full capacity (Danske Elværker 1995). In the calculations, 50% capacity utilisation is assumed. The efficiencies of the plants are for electricity production only, since co-production of heat is not relevant for a marginal power plant, for reasons stated above. For windmills, roughness class 1.5 is assumed giving 29% of the theoretical maximum capacity.

Table 3.1

Calculation of production cost per MWh for modern electricity production technologies.

Fuel type	Plant type	Effi-ciency	Life time	Product per year	Capital investment		Operation and maintenance		Fuel			Total cost
	MW	%	Years	MWh/y	DKK /MW	DKK MWh	% of investment per year	DKK/ MWh	Calorific value in MJ/kg	Price in DKK/kg	Cost in DKK/ MWh	DKK/ MWh
Hard coal	400	47	30	1.75E6	14E6	110	3.2	59	25.1	0.275	84	253
Natural gas	15	36	25	6.6E4	9E6	81	2.5	59	39.6 (MJ/m³)	1.296 (/m³)	327	467
Natural gas	250 CC*	54	30	1.1E6	9E6	68	2.5	34	39.6 (MJ/m³)	1.296 (/m³)	222	324
Heavy fuel oil	15	43	25	6.6E4	11E6	99	-	100**	40.6	0.69	142	341
Biomass	250* CFB	45	30	1.1E6	14E6	110	4	73	17.5	0.53	240	423
Wind	0.6	-	20	1500	11E6	216	1.5	36	-	0	0	252

* CC: Combined Cycle in which a natural gas driven turbine and another turbine driven from steam produced from the exhaust gas of the gas turbine. CFB: Circulating Fluid Bed. Technology at experimental stage.

** Authors' estimate. Total cost 250-320 DKK/MWh according to Hammar (1997) exc. capital goods.

From the calculations in table 3.1, the marginal technology would, under standard conditions, be hard coal or wind power. However, wind power cannot at present be regarded as an unconstrained technology, see section 3.2.2. Due to the lower capital costs required, gas fired plants may also become the marginal technology under periods of high interest rates, as has been the case in the U.K. recently.

3.2.4 Conclusion

Provided a deregulated electricity market with adequate transmission capacities – implying the same marginal technology all over EU – and provided that the EU emission targets do not generally limit the use of hard coal, coal condensing power will be the EU marginal since it has the lowest cost of the unconstrained technologies. However, as the emission targets are tightened, and the electricity consumption continues to rise, installation of new coal power plants may be limited, as is currently the case in the Nordic countries (Nordel 1996). The current marginal technology in the Nordic electricity system is therefore natural gas power.

3.3 Hard coal marginal electricity production

Lower calorific value of coal

Hard coal is not a well-defined substance, but is a composition of primarily carbon and other components such as hydrogen, oxygen, nitrogen, sulfur, ash and moisture. Eurostat (1997b) define this substance as hard coal if the higher calorific value is above 24 MJ/kg wet and ash free. Below that value it is called lignite. Other references (e.g. OECD 1997) may use other definitions, but the references are fairly comparable. Based on the Eurostat (1997a) 1994 consumption data of 198 10^9 kg on a mass basis and 115 Mtoe (1 toe = 41.87 GJ) on an energy basis, the European average hard coal can be calculated to have a lower calorific value of 24.3 MJ/kg. This value is a little lower than expected, compared to e.g. information given in Frischknecht *et al.* (1996) for the UCPTE countries.

Coal inputs

Modern condensing coal power plants have an efficiency of 47% (Energistyrelsen 1995) and thus needs 88 g of this average hard coal per MJout or 315 g/kWh.

CO_2 emissions

Using the value of 94 g CO_2 per MJ lower calorific value (Eurostat 1997c), the CO_2 emission can be calculated to 200 g/MJout or 720 g/kWh.

SO_2, NO_x, and particle emissions calculated from emission limits

The coal marginal technology will be used for extra demand of energy on a long-term basis and in practice this means that more plants will have to be built. Therefore, modern technology can be assumed that fulfils current emission limits - as defined in EU 88/603 (European Commission 1988). EU 88/603 regulates all combustion plants larger than 50 MW thermal power. New public power plants fired by solid fuels are usually larger than 500 MW thermal power or approximately 200 MW electrical power (Frischknecht *et al.* 1996). The following limits of emissions applies: 0.4 g SO_2, 0.65 g NO_x, and 0.05 g particles per m^3 exhaust gas.

Since the emission limits for SO_2, NO_X and particles are given in relation to the amount of exhaust gas, this amount must be known. It may be calculated by stoechiometry or from the heating value of the coal according to a formula given by Frischknecht *et al.* (1996):

$$1000\,(0.898 \times 0.239 \times H_U + 1634)/990$$

H_U is the lower calorific value in MJ/Mg and the exhaust gas amount will be in m^3/Mg. Frischknecht *et al.* (1996) do not explain the equation, but verification by stochiometric calculations of different compositions of coal shows that it is accurate within a few percent. We have therefore applied it for this study.

Using the above formulae with the calorific value 24300 MJ/Mg, the amount of exhaust gas can be calculated to 6.9 m^3 per kg coal. An unknown part of this - maybe 10% - is steam from hydrogen and evaporated moisture. However, in a modern power plant, a large part of the steam and evaporated moisture will condense (*e.g.* 75% at 65 °C exhaust temperature by vapour pressure (Kaye & Laby 1973)). Furthermore, an amount of surplus air (typically 6%) should be added. The corrections for condensed steam and surplus air work in opposite directions and are therefore likely to even out each other, so that a rough value for exhaust gas of 7 m^3/kg can be used for further calculations. This value corresponds well with the values provided by Frischknecht *et al.* (1996).

The exhaust output is then 0.62 m^3/MJ_{out} or 2.2 m^3/kWh and the resulting emissions according to the above emission limits will be 0.25 g SO_2, 0.40 g NO_x, and 0.03 g particles per MJ_{out} or 0.89 g SO_2, 1.45 g NO_x, and 0.11 g particles per kWh.

Other emissions

All other emissions are taken from Frischknecht *et al.* (1994). Since most of the power plants are situated in Germany (Germany stands for 28 percent of the electricity produced in EU15 by hard coal. United Kingdom stands for 32 percent but is not included in UCPTE.), the data for Germany were chosen as representative for the combustion of coal.

In order to simplify the inventory calculations, all NMVOC (non-methane volatile organic compounds) were aggregated to one value. The emissions were calculated according to the inputs of fuel.

Emission of heavy metals origin from trace elements in the coal the amount of which depends on the origin of the coal. Furthermore, the heavy metal emission depends on the ability of the power plants particle control system to bind metals, and particle control have been improved in the recent years. Hg is for example an important toxic heavy metal for which Frischknecht *et al.* provide the emission factor 7.6 g/TJ_{in} for Germany used in this study. CORINAIR (1996) suggest the interval 0.8 – 8 g/TJ_{in} (converted by the authors) indicating that the value used is somewhat overestimated. This is also consistent with the statement of Frischknecht *et al.* (1994) that the Hg content in German coal is rather high.

Resulting data

The resulting data are presented in Table 3.2.

Table 3.2

Data for hard coal marginal electricity per MJ_{out} from power plant.

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
Resources:				
Aluminium (Al)	g			1.77E-04
Calcium carbonate ($CaCO_3$)	g		*	3.10E-04
Clay	g			6.63E-05
Crude oil				2.50
Crude oil, feedstock	g			1.50E-05
Hard coal *	g			1.45E+01
Iron (Fe)	g			1.84E-04
Brown coal (lignite)	g			1.19E-00
Manganese (Mn)	g			1.04E-06
Natural gas	g			1.41E-01
Sodium chloride (NaCl)	g			3.09E-04
Soft wood, dry mass	g			4.04E-02
Unspecified biomass	g			8.50E-10
Unspecified fuel	MJ			1.77E-06
Uranium (U)	g			8.08E-05
Water for hydro power (8.36E-06 MJ/g)	g			2.61E-00
Water, in ground	g			3.99E-06
Water, surface-water	g			8.14E-08
Water, unspecified	g			2.79E+04
Emissions to air:				
Aldehydes, unspecified	g	2.78E-06		2.78E-06
Ammonia (NH_3)	g	1.00E-05		1.00E-05
Antimony (Sb)	g		3.41E-07	3.41E-07
Aromates, C9-C10	g	4.06E-05		4.06E-05
Arsenic (As)	g	5.50E-08	2.45E-06	2.51E-06
Benzo(a)pyrene	g	3.19E-09	4.26E-10	3.61E-09
Boron (B)	g		3.34E-04	3.34E-04
Cadmium (Cd)	g	5.60E-09	1.49E-07	1.55E-07
Carbon dioxide (CO_2)	g	1.19E+01	2.00E+02	2.12E+02
Carbon monoxide (CO)	g	2.82E-02	0.001065	2.93E-02
Chromium (Cr)	g	2.78E-08		2.78E-08
Chromium(Cr^{3+})	g		1.81E-06	1.81E-06
Cobalt (Co)	g		1.00E-06	1.00E-06

* As raw hard coal before sulfur cleaning.

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... Table 3.2 continued from previous page: Emissions to air.

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
Copper (Cu)	g	5.50E-08	1.98E-06	2.04E-06
Dioxin	g		1.07E-11	1.07E-11
Heavy metals, unspecified	g	1.08E-17		1.08E-17
Hydrocarbons (HC)	g	1.27E-02		1.27E-02
Hydrogen chloride (HCl)	g	7.00E-04	1.56E-02	1.63E-02
Lead (Pb)	g	5.50E-08	4.30E-06	4.36E-06
Magnesium (Mg)	g		2.34E-04	2.34E-04
Manganese (Mn)	g		2.77E-06	2.77E-06
Mercury (Hg)	g	2.30E-07	1.62E-05	1.64E-05
Metals, unspecified	g	2.21E-06		2.21E-06
Methane (CH_4)	g	1.10E-00	2.13E-03	1.10E-00
Molybdenum (Mo)	g		1.13E-06	1.13E-06
Nickel (Ni)	g	4.10E-08	2.17E-06	2.21E-06
Nitrogen oxides (NOx)	g	1.63E-01	4.00E-01	5.63E-01
Nitrous oxide (N_2O)	g	1.37E-04	1.07E-03	1.20E-03
NMVOC, el-coal	g		4.26E-03	4.26E-03
NMVOC, diesel engines	g	6.48E-03		6.48E-03
NMVOC, petrol engines	g	8.27E-13		8.27E-13
NMVOC, power plants	g	2.05E-03		2.05E-03
Organics	g			5.55E-06
PAH	g	5.55E-09		5.55E-09
Particles, unspecified	g	1.51E-02	3.00E-02	4.51E-02
Phosphorous (total)	g		1.70E-05	1.70E-05
Radioactive emission	kBq	7.51E-00	1.34E-03	7.51E-00
Selenium (Se)	g	2.00E-08	2.45E-05	2.45E-05
Strontium (Sr)	g		1.92E-06	1.92E-06
Sulphur dioxide (SO_2)	g	1.03E-01	2.50E-01	3.53E-01
Thallium (Tl)	g		8.52E-08	8.52E-08
Thorium (Th)	g		1.70E-07	1.70E-07
Tin (Sn)	g		3.83E-07	3.83E-07
Uranium (U)	g		1.28E-07	1.28E-07
Vanadium (V)	g	8.30E-08	2.34E-06	2.43E-06
VOC, diesel engines	g	3.07E-03		3.07E-03
VOC, heating, coal	g	1.11E-04		1.11E-04
VOC, heating, natural gas	g	8.65E-12		8.65E-12
Zinc (Zn)	g	2.80E-07	1.13E-05	1.16E-05
Emissions to water:				
Acids (H^+)	g	6.63E-05		6.63E-05
Aluminium (Al)	g	8.80E-05		8.80E-05
Aromates C9-C10, unspec.	g	1.27E-05		1.27E-05
BOD	g	1.11E-05		1.11E-05
Chlorate (ClO_3^-)	g		7.46E-04	7.46E-04

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... Table 3.2 continued from previous pag: .missions to air.

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
Chloride (Cl^-)	g	1.30E-00		1.30E-00
COD	g	2.21E-05		2.21E-05
Dissolved solids	g			8.80E-02
Dissolved organics	g	5.80E-13		5.80E-13
Fluoride (F^-)	g	2.64E-04		2.64E-04
Hydrocarbons (HC)	g	4.42E-05		4.42E-05
Iron (Fe)	g	1.76E-04		1.76E-04
Manganese (Mn)	g	8.80E-05		8.80E-05
Metals, unspecified	g	1.11E-05		1.11E-05
Nickel (Ni)	g	8.80E-06		8.80E-06
Nitrogen	g			2.84E-05
NH4-N	g			7.05E-05
NO3-N	g			6.45 E-07
Oil, unspecified	g	2.08E-04		2.08E-04
Phenol	g	1.45E-14		1.45E-14
Radioactive emission	kBq	1.24E-01		1.24E-01
Salt	g			8.80E-03
Strontium (Sr)	g	4.40E-04		4.40E-04
Sulphate (SO_4^{--})	g	5.99E-02		5.99E-02
Suspended solids	g			1.45E-03
Zn (zinc)	g	2.51E-05		2.51E-05
Wastes:				
Bulk waste	kg	4.62E-02		4.62E-02
Chemical waste	kg	3.55E-07		3.55E-07
Hazardous waste	kg	1.38E-03		1.38E-03
Industrial waste	kg	3.69E-04		3.69E-04
Mineral waste	kg	4.59E-06		4.59E-06
Radioactive waste	kg	2.41E-07		2.41E-07
Rubber	kg	5.39E-08		5.39E-08
Slags & ashes (energy production)	kg	2.29E-04	1.02E-03	1.25E-03
Sludge	kg	3.70E-14		3.70E-14

* The flue gas cleaning for sulphur dioxide implies an additional resource use of 3 g calcium carbonate. This input as well as the outputs from this flue gas cleaning (4.8 g gypsum and 1.3 g CO_2) are not included in this study.

3.4 Natural gas marginal electricity production

Lower calorific value of natural gas

Natural gas is a loosely defined substance, consisting of methane containing a small amount of heavier gases and nitrogen. The natural gas in this study mainly comes from the North Sea with a relatively well-defined composition with approx. 90% methane (CH_4). The lower calorific value used in this study is 39.6 MJ/m^3 (DONG 1996) and the density is 800 g/m^3.

Natural gas inputs

A modern natural gas fired power plant, as *e.g.* a combined cycle plant, has an efficiency of 45% (Energistyrelsen 1995) and thus needs 0.056 m^3 (45 g) per MJ_{out} or 0.202 m^3 (162 g) per kWh.

CO_2 emissions

Using the value of 56 g CO_2 per MJ lower calorific value (Eurostat 1997c), the CO_2 emission can be calculated to 124 g/MJ_{out} or 447 g/kWh.

NO_x and particle emissions calculated from emission limits

The natural gas marginal technology will be used for extra demand for energy on a long-term basis and in practice this means that more plants will have to be built and therefore modern technology can be assumed that fulfils present emission limits, *i.e.* as defined in EU 88/603 (European Commission 1988). For plants larger than 50 MW thermal power fired by gaseous fuels EU 88/603 sets the following limits of emissions per Nm^3 exhaust gas: 0.035 g SO_2, 0.35 g NO_x, 0.005 g particles. In practice the SO_2 level is close to zero (CORINAIR 1996) and therefore negligible.

Since the emission limits for NO_x and particles are given in relation to the amount of exhaust gas, this amount must be known. It may be calculated by stoechiometry assuming pure CH_4 (O'Callaghan 1993):

$$CH_4 + 2(1+a)(O_2 + (79/21)N_2) = CO_2 + 2H_2O + 2aO_2 + 2((1+a)79/21)N_2$$

where a is the part of excess air and 79/21 is the weight ratio of the non-reactive part of the air (nitrogen and argon) to oxygen in the air. For a = 0.05 (*i.e.* 5% excess air, a typical value) the equation becomes:

$$CH_4 + 2.1\ O_2 + 7.9\ N_2 = CO_2 + 2\ H_2O + 0.1\ O_2 + 7.9\ N_2$$

Due to Avogadro's law, this equation is valid for number of moles as well as for volume (m^3) of the gases. Then 1 m^3 CH_4 gives 11 m^3 exhaust gas at 5% excess air. Of the 2 m^3 steam, 75% will condense due to vapour pressure, assuming a modern condensing plant with 65 °C exhaust temperature (Kaye & Laby 1973), and then the amount of exhaust gas is 9.5 Nm^3 per m^3 CH_4. The calculations can be shown to give approximately the same result for natural gas.

The exhaust output is then 0.53 m^3/MJ_{out} or 1.92 m^3/kWh and the resulting emissions according to the above emission limits will be 0.19 g NO_x and 0.0027 g particles per MJ_{out} or 0.67 g NO_x and 0.0096 g particles per kWh.

Other emissions

Emission of SO_2 is negligible (CORINAIR 1996). All other emissions are from Frischknecht *et al.* (1994). For the NMVOC, agglomerated factors for toxicity and photochemical ozone formation potential were calculated.

Table 3.3
Data for natural gas marginal electricity per MJ_{out} from power plant.

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
Resources:				
Natural gas	g			4.51E+01
Crude oil	g			2.16E-01
Emissions to air:				
Benzo(a)pyrene	g		2.18E-08	2.18E-08
Carbon dioxide (CO_2)	g	6.90E-00	1.24E+02	1.31E+02
Carbon monoxide (CO)	g	7.50E-04	3.05E-02	3.13E-02
Dioxin	g		6.54E-14	6.54E-14
Mercury (Hg)	g		1.20E-07	1.20E-07
Methane (CH_4)	g	4.58E-03	4.36E-03	8.94E-03
Nitrogen oxides (NO_x)	g	3.25E-02	1.90E-01	2.23E-01
Nitrous oxide (N_2O)	g	1.02E-04	2.18E-04	3.20E-04
NMVOC, unspecified	g		6.50E-03	6.50E-03
NMVOC, el-natural gas	g	3.70E-03		3.70E-03
Particles, unspecified	g		2.70E-03	2.70E-03
Sulphur dioxide (SO_2)	g	5.21E-04		5.21E-04
Wastes:				
Unspecified hazardous	kg	1.64E-02		1.64E-02
Unspecified industrial	kg	1.18E-01		1.18E-01

3.5 Average European electricity production 1994

For the European average electricity scenario the electricity production in the European Union (EU-15) is considered. The countries are presented in annex B. The scenario includes electricity production from public power plants and from private producers, both excluding heat production by allocation according to exergy content. The data are from 1994 since this is the most recent year for which most types of statistical data were available.

Data sources

Eurostat (1997b & c) give combined data for electricity and heat production by fuel type (nuclear, hydro, coal etc.). These have been checked against Eurostat Energy Balance Sheets (Eurostat 1997a) and with Energy Statistics of OECD Countries, 1994-95 (OECD 1997). Minor differences has been observed. Most remarkable is that OECD (1997) reports an approx. 15% higher natural gas consumption and approx. 20% lower renewable consumption than Eurostat (1997a).

The distribution of fuels is shown in table 3.4.

Table 3.4

Distribution of fuels for average European electricity 1994.

	kg_{in} per MJ_{out}	Heating value MJ/kg	MJ_{in} per MJ_{out}
Hard coal*	0.0246	29.5	0.73
Lignite**	0.0320	10	0.32
Fuel oil**	0.0052	42.5	0.22
Natural gas**	0.0048	48.5	0.23
Renewable**	-	-	0.05
Hydropower**	-	-	0.14
Nuclear power	-	-	0.37

* A distribution of 85% from closed mines and 15% from open mines was used, according to information from Frischknecht *et al.* (1996).

** Some aggregation of fuels has been done because emissions from power plants were not available on that detailed level:
- Lignite includes briquettes.
- Fuel oil include gasoil and refinery gas.
- Natural gas includes gas derivatives. The input in kg has been obtained by multiplying the amount in Nm^3 with the density 0.8 kg/Nm^3.
- Renewable include waste incineration.
- Hydropower includes wind and geothermal power.

CORINAIR data preferred

Eurostat and CORINAIR was chosen as the best available sources, of which CO_2, SO_2 and NO_X are measured and checked by authorities. Data from CORINAIR were preferred because they cover both public and private producers whereas Eurostat only cover public power plants (Eurostat 1997d). As private producers transform approximately 14% of the fuel for electricity production (Eurostat 1997a) they cannot be regarded as negligible. Also data from many countries are more recent in CORINAIR than in Eurostat (1997c).

Exception for Spain, Italy, Portugal and Finland

The countries Spain, Italy, Portugal and Finland constitute an exception because CORINAIR only give total amounts for the transformation industry - i.e. including refineries and mining. Therefore, for these countries, Eurostat (1997c) data were used, but corrected to account for private producers, see table 3.5. These Eurostat data are a little older (1992, 1993) than the CORINAIR data.

Table 3.5
Corrections of Eurostat emission data for Spain, Italy, Portugal and Finland to include private electricity producers.

Country	Fuel	Eurostat, input in ktoe 1994			Correction (Total/Public)	
		Public	Private	Total	Factor	Relevant for*
Spain	Solids	13893	154	14047		
	Petro	1853	538	2391		
	Sub-sum	15746	692	16438	1.04	SO2
	Natural gas	187	542	729		
	Renewable	750	18	768		
	Sum	16683	1252	17935	1.08	NOx, CO
Italy	Solids	4361	3	4364		
	Petro	21501	2273	23774		
	Sub-sum	25862	2276	28138	1.09	SO2
	Natural gas	5606	1011	6617		
	Renewable	349	0	349		
	Sum	31817	3287	35104	1.10	NOx, CO
Portugal	Solids	2576	0	2576		
	Petro	1408	272	1680		
	Sub-sum	3984	272	4256	1.07	SO2
	Natural gas	0	39	39		
	Renewable	138	0	138		
	Sum	4122	311	4433	1.08	NOx, CO
Finland	Solids	4407	132	4539		
	Petro	136	152	288		
	Sub-sum	4543	284	4827	1.06	SO2
	Natural gas	1077	303	1380		
	Renewable	412	3250	3662		
	Sum	6032	3837	10382	1.72	NOx, CO

N.B.: Eurostat data for CO_2 are given for private producers as well, so no correction is necessary for CO_2, except for Finland, where the Eurostat data include also pure district heating. To adjust for the 513 ktoe to district heating out of the total 6207 ktoe, a factor of 0.92 was used on the Eurostat CO_2 data for Finland. For other emissions than CO_2, SO_2, NO_x and CO, corrections for missing data have been made by extrapolating the emission data for those countries for which data were available (see table Energy1b in annex A).
The factors for SO_2 excludes gas and renewable fuels, because these are assumed to contribute very little to the SO_2 emission compared to the solid and petro fuels. This assumption could be questioned for the renewable fuels, but it is however verified with data from CORINAIR (1996) and Energistyrelsen (1995).

Comparison to UCPTE

Data were verified against the values in Frischknecht *et al.* (1996), which cover the UCPTE countries. These countries form part of the EU so that Denmark, Ireland, Portugal, Finland, Sweden and U.K. is in EU but not in UCPTE. Poland, Switzerland and former Yugoslavia is in the UCPTE but not in EU-15. The UCPTE electricity production is approximately 75% of EU production.

CO_2, SO_2, NO_x, CH_4, NMVOC and N_2O emissions	Emission data for CO_2, SO_2, NO_x, CH_4, NMVOC and N_2O have mainly been taken from CORINAIR (1996 & 1997) and validated against data from Eurostat (1997c) whenever possible (see table Energy1b.xls in annex A). Renewable fuels are considered CO_2 neutral because only that amount of CO_2 is released, which was accumulated during the growth of the plants. Emissions from hydropower, wind power and geothermal power are assumed to be negligible.
Particle emissions	For particle emissions the Eurostat (1997c) data are used.
Other emissions	Using Eurostat (1997 b & c) data as a basis, other emissions as well as pre-combustion emissions have been calculated from Frischknecht *et al.* (1996).
Allocation between electricity and heat	Allocation between electricity and heat may be performed on the basis of the relative economic value of these two products. As we did not have any generally applicable economic data, we have used the exergy in the output as an approximation for the economic value. This means that heat is calculated with the factor 0.33 compared to electricity (factor 1). This method is used in the ExternE project (Schleisner & Nielsen 1997) and has also been used by Frischknecht *et al.* (1996). For that part of the electricity system which produces heat (*i.e.* excluding nuclear, wind and hydro power) the values 3773 PJ electricity output and 441 PJ heat output (Eurostat 1997a) result in an allocation of 96% to electricity and 4% to heat.
Corrections for fuel type	Since the data dividing the production according to fuel type cover both electricity and heat production, it may be relevant to adjust this distribution over fuels, to take into account that the ratio between heat and electricity is not evenly distributed over fuel types. Based on data from OECD (1997) we have calculated that the production ratio of heat to total energy production is slightly higher for hard coal fired plants (approximately 7%) and plants based on biomass and waste (approximately 20%) compared to the average 5%. This means that when allocating between electricity and heat, slightly less emissions should be allocated to the electricity from plants fired with hard coal, biomass and waste and slightly more emissions to the electricity from the other fuels. However, since electricity and heat from biomass and waste constitute only 4% of the total production in EU, and the other corrections are in the range of 2%, we have found these adjustments unnecessary in view of the uncertainty on the underlying statistical information and the uncertainty of the allocation procedure itself.
Resulting data	Resulting data are presented in table 3.6.

Table 3.6
Data for average European electricity 1994 per MJ_{out} from power plant.

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
Resources:				
Aluminium (Al)	g			5.04E-05
Brown coal (lignite)	g			3.28E+01
Calcium carbonate ($CaCO_3$)	g			8.83E-05
Clay	g			1.89E-05
Crude oil	g			7.37E-00
Crude oil, feedstock	g			4.19E-06
Hard coal *	g			4.10E+01
Iron (Fe)	g			5.23E-05
Manganese (Mn)	g			2.92E-07
Natural gas	g			5.15E-00
Sodium chloride (NaCl)	g			8.82E-05
Soft wood, dry mass	g			2.07E-02
Unspecified biomass	g			6.92E-03
Unspecified fuel	MJ			4.95E-07
Uranium (U)	g			3.00E-03
Water, in ground	g			1.12E-06
Water, surface-water	g			2.28E-08
Water, unspecified	g			4.0E+06
Water for hydro power (8.36E-06 MJ/g)	g			1.68E+04
Emissions to air:				
Aldehydes, unspecified	g	7.78E-07		7.78E-07
Ammonia (NH_3)	g	5.29E-06		5.29E-06
Antimony (Sb)	g		1.59E-06	1.59E-06
Aromates, C9-C10	g	2.08E-05		2.08E-05
Arsenic (As)	g	1.97E-07	4.09E-06	4.29E-06
Benzene (H6C6)	g	1.78E-04		1.78E-04
Benzo(a)pyrene	g	1.63E-09	5.88E-09	7.52E-09
Boron (B)	g		1.26E-03	1.26E-03
Cadmium (Cd)	g	3.62E-07	1.83E-06	2.19E-06
Carbon dioxide (CO_2)	g	8.90E-00	1.12E+02	1.21E+02
Carbon monoxide (CO)	g	1.25E-02	8.40E-02	9.65E-02
Chromium (Cr)	g	7.78E-09		7.78E-09
Chromium(Cr^{3+})	g	2.96E-07	7.04E-06	7.34E-06

* As raw hard coal before sulfur cleaning.

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... Table 3.6 continued from previous page: Emissions to air.

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
Cobalt (Co)	g		3.11E-06	3.11E-06
Copper (Cu)	g	1.00E-08	1.91E-05	1.91E-05
Cyanide (CN^-)	g	1.79E-06		1.79E-06
Dioxin	g	2.64E-11	5.23E-12	3.17E-11
Heavy metals, unspecified	g	3.03E-18		3.03E-18
Hydrocarbons (HC)	g	3.58E-03		3.58E-03
Hydrogen chloride (HCl)	g	5.00E-04	6.07E-03	6.57E-03
Hydrogen flouride (HF)	g	9.49E-05	1.67E-05	1.12E-04
Hydrogen sulphide (H_2S)	g	1.33E-06		1.33E-06
Lead (Pb)	g	1.20E-06	1.46E-05	1.58E-05
Magnesium (Mg)	g		3.71E-04	3.71E-04
Manganese (Mn)	g		6.36E-06	6.36E-06
Mercury (Hg)	g	1.72E-07	6.74E-06	6.91E-06
Metals, unspecified	g	6.30E-07		6.30E-07
Molybdenum (Mo)	g	4.00E-09	1.75E-06	1.75E-06
Nickel (Ni)	g	1.36E-05	9.11E-05	1.05E-04
Nitrogen oxides (NOx)	g	7.26E-02	2.70E-01	3.43E-01
Nitrous oxide (N_2O)	g	1.02E-04	4.40E-03	4.50E-03
NMVOC, el-european base load	g		2.60E-03	2.60E-03
NMVOC, diesel engines	g	1.89E-03		1.89E-03
NMVOC, heating, oil	g	5.36E-02		5.36E-02
NMVOC, power plants	g			1.05E-03
PAH	g	1.56E-09		1.56E-09
Particles, unspecified	g	2.72E-02	3.90E-02	6.62E-02
Phosphorous (total)	g		8.36E-06	8.36E-06
Radioactive emission	kBq	2.61E+02	5.60E-04	2.61E+02
Selenium (Se)	g	1.00E-08	1.91E-05	1.91E-05
Strontium (Sr)	g		1.30E-05	1.30E-05
Sulphur dioxide (SO_2)	g	6.28E-02	9.00E-01	9.63E-01
Thallium (Tl)	g		3.54E-08	3.54E-08
Thorium (Th)	g		2.05E-07	2.05E-07
Tin (Sn)	g		2.87E-07	2.87E-07
Uranium (U)	g		1.97E-07	1.97E-07
Vanadium (V)	g	2.90E-06	3.23E-04	3.26E-04
VOC, diesel engines	g	8.60E-04		8.60E-04
VOC, heating, coal	g	3.11E-05		3.11E-05
VOC, heating, natural gas	g	2.43E-12		2.43E-12
Zinc (Zn)	g	7.36E-06	2.65E-05	3.38E-05
Emissions to water:				
Acids (H^+)	g	1.89E-05		1.89E-05
Aluminium (Al)	g	2.47E-05		2.47E-05
Arsenic (As)	g	7.46E-07		7.46E-07
Aromates C9-C10, unspecified	g	6.51E-06		6.51E-06

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... *Table 3.6 continued from previous page: Emissions to air.*

Flows	Unit	Amount pre-combustion	Amount power plant	Amount total
BOD	g	3.15E-06		3.15E-06
Cadmium (Cd)	g	3.62E-07		3.62E-07
Chromium(Cr^{3+})	g	2.00E-07	3.66E-04	3.66E-04
Chlorate (ClO_3^-)	g	5.61E-01	3.29E-05	5.61E-01
Chloride (Cl^-)	g	5.40E-06		5.40E-06
COD	g	6.30E-06		6.30E-06
Dissolved organics	g	1.62E-13		1.62E-13
Fluoride (F^-)	g	1.49E-04		1.49E-04
Hydrocarbons (HC)	g	2.29E-05		2.29E-05
Iron (Fe)	g	5.13E-02		5.13E-02
Lead (Pb)	g	2.71E-06		2.71E-06
Manganese (Mn)	g	2.47E-05		2.47E-05
Metals, unspecified	g	3.15E-06		3.15E-06
Nickel (Ni)	g	4.69E-06		4.69E-06
Nitrogen	g			6.72E-04
NH4-N	g			3.59E-04
NO3-N	g			1.91E-07
Oil, unspecified	g	6.22E-03		6.22E-03
Phenol	g	4.06E-15		4.06E-15
Phosphate (PO_4^{3-})	g	1.81E-05		1.81E-05
Radioactive emission	kBq	7.22E-02		7.22E-02
Strontium (Sr)	g	1.23E-04		1.23E-04
Sulphate (SO_4^{--})	g	3.42E-01	8.82E-05	3.42E-01
Zn (zinc)	g	1.14E-04		1.14E-04
Wastes:				
Bulk waste	kg	1.30E-02		1.30E-02
Chemical waste	kg	9.94E-08		9.94E-08
Hazardous waste	kg	2.47E-03		2.47E-03
Industrial waste	kg	1.40E-02		1.40E-02
Mineral waste	kg	1.29E-06		1.29E-06
Radioactive waste	kg	8.87E-06		8.87E-06
Rubber	kg	1.51E-08		1.51E-08
Slags & ashes	kg	6.98E-05		6.98E-05
Slags & ashes (energy production)	kg	1.14E-04	2.87E-03	2.98E-03
Sludge	kg	1.00E-09	3.36E-06	3.36E-06

3.6 Distribution losses

The above reported electricity data are all referring to MJ_{out} from the power plants. Transmission losses depend on the end voltage used by the electricity consumer. Gärdenäs *et al.* (1997) report a 9% loss for household electricity (less than 400 V), a 6% loss for industrial users at 10 kV and a 3% loss for industrial users at 130 kV. In the studied packaging systems, we have calculated with a 9% loss for most processes. For aluminium production through electrolysis and steel recycling in electric arc furnaces (the most electricity intensive processes), we calculated with a 3% loss. In general, this means we have probably overestimated the electricity consumption by a few percent.

4 Thermal energy

4.1 Fuel types used in industry

Unless data on fuel use are available for the specific processes involved, the fuel type must be estimated from statistics. Table 4.1 gives the distribution of fuels consumed in industry in 1994 specified per industrial sector and country for the most relevant sectors and countries.

4.2 Industrial coal combustion

Data representing large industrial boilers (1-10 MW) are taken from Frischknecht *et al.* (1996). The data are presented in annex A.

4.3 Oil combustion

Small boilers

Data representing combustion of light fuel oil in small boilers (10-100 kW) are taken from Frischknecht *et al.* (1996). Emission of SO_2 has been corrected from a sulphur-content of 0.14% in the original source to 0.05% S (Statoil & Texaco 1996). The reduced value is 0.02 g per MJ compared to 0.06 g per MJ. The data are presented in annex A.

Industrial boilers

Data representing combustion of heavy fuel oil in industrial boilers (1 MW) are taken from Frischknecht *et al.* (1996). Emission of SO_2 has been corrected from a sulphur-content of 2.6% in the original source to 0.65% S (Statoil & Texaco 1996). Emission of particles is also dependent to some extent on the sulphur content. This has been taken into account by using an equation from Frischknecht *et al.* (1996):

$$\text{Emission of particles} = 1.25\,S + 0.38$$

where S is the sulphur content in percent, the emission of particles is given in kg per 1000 l.

This gives an adjustment of the emission of particles from 50 to 29 kg per TJ. The adjustment of the emission of SO_2 gives a reduction from 1.2 g per MJ to 0.3 g per MJ.

The resulting data are presented in annex A.

4.4 Combustion of liquid petroleum gas (LPG)

Data are taken from CORINAIR (1996). The data are presented in annex A.

Table 4.1
Fuels consumed in industry 1994 in EU and a specification for some countries and sectors of industry relevant for this study (from Eurostat 1997a).

Country	Fuels	Iron & steel industry		Non-ferrous metal industry		Chemical industry		Food, drink & tobacco		Industry, total	
		ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
EU 15	Solids	23748	53	863	22	3265	11	1249	8	40254	23
	Gasoil	*422*	*11*	*171*	*13*	*611*	*10*	*1444*	*25*	*11067*	*27*
	Fuel oil	*3232*	*83*	*856*	*66*	*5080*	*83*	*4002*	*68*	*25039*	*62*
	LPG	*235*	*6*	*272*	*21*	*409*	*7*	*403*	*7*	*4344*	*11*
	Petro, total	3893	9	1301	33	9133	30	5854	37	49367	28
	* Natural gas	16759	38	1812	46	17651	59	8835	55	78404	44
	** Renewable	n.a.	-	n.a.	-	n.a.	-	n.a.	-	9165	5
	Sum	44400	100	3976	100	30049	100	15938	100	177190	100
Germany	Solids	6227	49	161	18	1708	20	373	11	11755	28
	Gasoil	*117*	*8*	*79*	*58*	*250*	*27*	*730*	*57*	*3781*	*45*
	Fuel oil	*1323*	*91*	*26*	*19*	*685*	*73*	*455*	*35*	*3692*	*44*
	LPG	*19*	*1*	*32*	*23*	*2*	*0*	*97*	*8*	*948*	*11*
	Petro, total	1460	12	139	16	955	11	1283	38	8703	21
	* Natural gas	4931	39	590	66	5822	69	1696	51	21003	50
	** Renewable	n.a.	-	n.a.	-	n.a.	-	n.a.	-	258	1
	Sum	12618	100	890	100	8485	100	3352	100	41719	100
France	Solids	3638	65	61	10	336	12	157	6	5368	22
	Gasoil	*17*	*17*	*10*	*4*	*0*	*0*	*44*	*5*	*1841*	*35*
	Fuel oil	*81*	*83*	*79*	*29*	*562*	*100*	*697*	*77*	*2772*	*52*
	LPG	*0*	*0*	*188*	*68*	*0*	*0*	*161*	*18*	*693*	*13*
	Petro, total	98	2	278	44	600	22	903	32	7004	29
	* Natural gas	1900	34	300	47	1829	66	1727	62	10405	43
	** Renewable	n.a.	-	n.a.	-	n.a.	-	n.a.	-	1421	6
	Sum	5636	100	639	100	2765	100	2787	100	24198	100
Denmark	Solids	1	2	0	0	2	3	79	15	341	18
	Gasoil	*8*	*100*	*0*	*0*	*10*	*24*	*87*	*41*	*357*	*44*
	Fuel oil	*0*	*0*	*0*	*0*	*29*	*71*	*108*	*51*	*393*	*49*
	LPG	*0*	*0*	*0*	*0*	*2*	*5*	*16*	*8*	*60*	*7*
	Petro, total	9	20	0	0	45	56	213	41	889	46
	* Natural gas	34	77	2	100	33	41	223	43	613	32
	** Renewable	n.a.	-	n.a.	-	n.a.	-	n.a.	-	101	5
	Sum	44	100	2	100	80	100	515	100	1944	100
Sweden	Solids	921	63	0	0	7	4	18	6	1241	17
	Gasoil	*27*	*9*	*8*	*26*	*40*	*31*	*38*	*21*	*430*	*24*
	Fuel oil	*130*	*43*	*6*	*19*	*82*	*64*	*101*	*56*	*995*	*55*
	LPG	*146*	*48*	*17*	*55*	*6*	*5*	*41*	*23*	*396*	*22*

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... Table 4.1 continued from previous page: Emissions to air.

Country	Fuels	Iron & steel industry ktoe	%	Non-ferrous metal industry ktoe	%	Chemical industry ktoe	%	Food, drink & tobacco ktoe	%	Industry, total ktoe	%
	Petro in all	304	21	32	100	129	69	181	59	1825	24
	* Natural gas	236	16	0	0	50	27	108	35	470	6
	** Renewable	n.a.	-	n.a.	-	n.a.	-	n.a.	-	3970	53
	Sum	1461	100	32	100	186	100	307	100	7506	100

* The figures include derived gas, which are almost solely used in the iron & steel industry.

** Eurostat (1997a) does not specify on sector but is provided here for the total industry sector to assess sensitivity. Renewable fuels are presumably mainly used in branches producing surplus biomass as *e.g.* the paper industry (Sweden).

4.5 Combustion of natural gas

Data are taken from Frischknecht *et al.* 1996. The data are presented in annex A.

4.6 Combustion of bark and peat biomass

Bark and peat are in this study used as a fuels in the pulp and paper industry. Site specific data for bark combustion in a Swedish paper mill (Hylte Bruk) have been used. Data for peat combustion were found in Christensen 1991. The data are presented in annex A.

4.7 Waste incineration

Data for waste incineration are calculated for aluminium, cardboard/corrugated board, glass, paper, PE, PET, PP, steel, tinplate, and wood (see table 4.2).

Heat and electricity production

Data for the co-production of heat and electricity are based on SK Energi (1994) on Danish waste incineration plants in 1992. The energy reported is ex incineration plant. Waste incineration plants in Denmark produce both district heat and electricity or district heat only. In 1992, 66.5% of the energy came from plants producing district heating only. Based on data from SK Energi (1994) the average heat and electricity outputs are calculated to, respectively, 76.8% and 3.9% of the lower calorific value of the incoming material. As organic, combustible materials are assumed to produce 2% soot, only 98% of these materials contribute to energy production.

Non-combustible materials

Non-combustible materials such as glass consume energy, because the slag is 300°C when it leaves the plant. The energy loss due to non-combustible materials is calculated based on the specific heat capacities and amounts of the materials and a temperature difference of 275°C.

Cardboard, glass, plastics, paper, steel

Data for cardboard, glass, PE, PET, PP, paper, and steel are taken from the EDIP database (Frees and Pedersen, 1996). The lower calorific values are: Cardboard and paper 15 MJ/kg, PE and PP 43 MJ/kg, PET 31.4 MJ/kg. Air emissions from incineration of cardboard, paper, and PET have been corrected because of an error in the structural formula of PET and cellulose in the EDIP database.

Wood

Air emission data for wood are based on 1% ash and a composition of 50wt% C, 44wt% O and 6wt% H of the dry ash free wood (Dalager *et al.* 1995). The consumption of auxiliary materials is based on EDIP unit process database. The lower heating value of dry wood is 18.3 MJ/kg (Dalager *et al.* 1995).

Aluminium

Incineration of thin plate aluminium (cans) liberates energy as aluminium is oxidised ($2Al + 1½O_2 \rightarrow Al_2O_3$) (Tillman *et al.*, 1991). The lower heating value of aluminium is 30.9 MJ/kg calculated from the heat of formation for Al_2O_3.

Tinplate

Calculated from the heat of formation for Fe_3O_4, the lower heating value of tinplate is 6.6 MJ/kg. During incineration of thin tinplate (in caps and steel cans), 20% of the iron is assumed to oxidise to Fe_3O_4. The tin from the thin tin layer diffuses into the steel during the incineration process. Two different phases develops during the process - the layer closest to the steel consists of $FeSn_2$ while the outside layer consists of FeSn (Ravnborg and Johansen, 1989). Therefore tin follows the steel fraction in the incineration plant and ends in the slag as $FeSn_2$ and FeSn.

Table 4.2
Waste incineration in Danish incineration plants. All figures are given per kg material incinerated.

	Unit	PET	PE & PP	Paper & board	Wood (DM)	Glass	Tin-plate	Aluminium
Auxiliary materials:								
$Ca(OH)_2$ (flue gas cleaning)	g	17.6	17.6	17.6	17.6	17.6	17.6	17.6
Water (flue gas cleaning)	g	243	243	243	243	243	243	243
Energy use:								
Electricity	kWh	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Co-products:								
Heat	MJ	23.6	32.4	11.3	13.8	-0.18	0.88	23.7

Continues on next page...

... Table 4.2 continued from previous page: Emissions to air.

	Unit	PET	PE & PP	Paper & board	Wood (DM)	Glass	Tin-plate	Aluminium
Electricity	MJ	1.20	1.64	0.57	0.57	-0.009	0.046	1.20
Air emissions:								
Dioxin	ppm	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NO_x	g	1.2	1.2	1.2	1.2	1.2	1.2	1.2
CO_2	g	2410	3065	1590	1776	-	-	-
CO	g	8	10	5	6	-	-	-
H_2O	g	496	1260	544	522	-	-	-
Fe	g						0.1	
Al_2O_3	g							0.2
Waste:								
Slag and ashes	kg	0.020	0.020	0.020	0.030	1	1.076	1.89
Wastewater to treatment	g	243	243	243	243	243	243	243

System expansion

The district heat produced by waste incineration plants replace the average Danish household boiler, which is based on oil (60%) and natural gas (40%; Eurostat 1997a). The electricity replaced is assumed the same type that is supplied to the packaging system.

5 Transport by truck

5.1 Data availability

Preferably, the data for beverage distribution by truck should be based on the specific fuel consumption of trucks and on emission factors relating to trucks (size, age) and to driving modes (urban, rural, highway).

Data sources

The choise of data source was discussed in (Weidema *et.al.*, 1997). Several data sources was investigated and generally they suffered from the facts that emission factors were based on standard test cycle meassurements which dos not simulate real driving conditions and that the fuel consumption could not be specified, but was given according to the types of trucks dealt with by the data source. The conclusion was that preferably, the data for beverage distribution by truck should be based on the specific fuel consumption of trucks and on emission factors relating to trucks (size, age) and to driving modes (urban, rural, highway), if possible measured by a truck producer which is likely to bring the most updated and representative data. As explained following the conclusion could only partly be followed.

Truck types

The types of trucks, their size, age and technology and the driving modes have been obtained (Jacobsen 1997) as a part of the distribution scenarios, see section 5.2. For the empty packagings and their raw materials the information is often limited to the size of the trucks used.

Fuel consumption

It was not possible to obtain data for the specific fuel consumption by the distributors, but typical figures have been obtained from Volvo (de Val 1992, Rydberg 1997). The figures have been verified and adjusted against literature data, see section 5.3.

Emission factors

It was not possible to obtain sufficient information of emission factors by different driving modes and trucks from a truck producer, so CORINAIR data are used updated with recent emission standards (CORINAIR 1996, European Commision 1993), see section 5.4. The CORINAIR data was used because they are well documented and based on test cycle measurements simulating real driving conditions.

5.2 Distribution scenarios

5.2.1 Distribution of beverage

Four models

In Denmark, four models (Jacobsen 1997) can describe the distribution of beverage:

Model 1: Brewery → Central → Retail
Model 2: Brewery → Retail
Model 3: Brewery → Central → Wholesaler → Retail
Model 4: Brewery → Wholesaler → Retail

Three types of trucks

The beverage are delivered by three types of trucks as shown in table 5.1 (Jacobsen, 1997). All trucks run with turbo on light Diesel with less than 0.05% S.

Transport distances

The transport distances are provided in table 5.2. For returnable packagings, the trucks bring back the empty packagings by the same models as for the delivering. For disposable packagings, the used packagings are brought back to central stock or brewery by the distribution trucks and from there, they go to recycling.

Table 5.1

Types of trucks.

Truck type	Size	Max. volume [pallets]	Total mass [mg]	Aver-age [years]	Starts pr. trip	Rural	Urban	High-way
Type 1	Heavy	48	48 (37*)	3	2	40%	10%	50%
Type 2	Medium	18	20	4	10	30%	60%	10%
Type 3	Medium	33	25	4	9	30%	40%	30%

* Disposable PET bottles are distributed in lighter trucks (max. total weight 37 Mg).

Table 5.2

Transportation distance (km) by truck types 1 to 3.

Model	Fraction	Numeric distance * Truck type 1	Numeric distance * Truck type 2	Numeric distance * Truck type 3	Weighted distance * Truck type 1	Weighted distance * Truck type 2	Weighted distance * Truck type 3
1	46%	140	12	0	64.4	5.52	0
2a	3%	140	0	0	4.2	0	0
2b	19%	0	12	0	0	2.28	0
3	1%	140	12	150	1.4	0.12	1.5
4	31%	140	0	150	43.4	0	46.5
Total	100%				113.4	7.92	48

* Including return (way out: full bottles, way home: empty packaging).

The distribution from brewery to central stock or large customers takes place by heavy trucks, type 1, which starts full and returns with empty packagings. A small fraction, see model 2a table 5.2, is however delivered to small customers next to the brewery by medium size trucks type 2, as from central stock. The distribution from central stock takes place by medium size truck type 2 and the distribution from wholesaler takes place by medium size truck type 3. In these cases up to 10 customers are visited, so that the trucks successively unloads beverage and loads empty packagings.

Load constraints

Either volume or weight limits the load on the trucks. Based on table 5.3, it can be calculated that for glass and PET bottles delivered by truck type 1 and 2 the load is limited by the volume of the goods, while for aluminium and steel cans and for glass and PET bottles delivered by truck type 3 the load is limited by the weight of the goods (see also table 5.1). Even in the latter case, the percentage of full load may not be exactly 100 (see table 5.4), because only whole pallets are freighted.

Table 5.3
Gross weight of packagings and packed pallets.

	Gross weight of one full item kg	Gross weight of one empty item kg	Numbers per pallet	Gross weight per pallet, full kg	Gross weight per pallet, return kg
Glass, 33 cl, returnable	0.725	0.395	900	653	356
Glass, 25 cl, returnable	0.575	0.325	900	518	293
Glass, 33 cl, disposable	0.51	0.17	900	459	153
PET, 50 cl, returnable	0.64	0.14	960	614	134
PET, 50 cl, disposable	0.56	0.06	960	538	58
PET, 150 cl, returnable	1.87	0.37	240	449	89
PET, 150 cl, disposable	1.65	0.15	240	396	36
Al & Steel cans, 33 cl	0.36	0.03	2376	855	71
Al & Steel cans, 50 cl	0.55	0.05	1848	1016	92

Calculated loads

The trucks are loaded as shown in table 5.4. The average load for a whole trip from start to return is calculated and placed in categories for the ease of calculating fuel consumption and emissions, see section 5.3. These categories are expected to give sufficient certainty of the calculations as discussed in section 5.3.

Table 5.4

Load of trucks in distribution of beverage.

	Number of pallets	Start. kg	% of full load	Return [kg]	% of full load	Average load %	Load % category
Truck 1 (max. load 32000 kg):							
Glass, 33 cl, returnable	48	31300	98	17100	53	76	70
Glass, 25 cl, returnable	48	24900	78	14100	44	61	70
Glass, 33 cl, disposable	48	22000	69	7300	23	46	50
PET, 50 cl, returnable	48	29500	92	6400	20	56	50
PET, 150 cl, returnable	48	21600	67	4300	13	40	50
Al & Steel cans, 33 cl	37	31600	99	2600	8	54	50
Al & Steel cans, 50 cl	31	31500	98	2900	9	54	50
Truck 1 (max. load 25000 kg):							
PET, 50 cl, disposable	46	24700	99	2700	11	55	50
PET, 150 cl, disposable	48	19000	76	1700	7	41	50
Truck 2 (max. load 12000 kg):							
Glass, 33 cl, returnable	18	11700	98	6400	53	76	70
Glass, 25 cl, returnable	18	9300	78	5300	44	61	70
Glass, 33 cl, disposable	18	8300	69	2800	23	46	50
PET, 50 cl, returnable	18	11000	92	2400	20	56	50
PET, 50 cl, disposable	18	9700	81	1000	9	45	50
PET, 150 cl, returnable	18	8100	67	1600	13	40	40
PET, 150 cl, disposable	18	7100	59	650	5	32	40
Al & Steel cans, 33 cl	14	12000	100	1000	8	54	50
Al & Steel cans, 50 cl	11	11400	95	1000	9	52	50
Truck 3 (max. load 15000 kg):							
Glass, 33 cl, returnable	23	15000	100	8200	55	77	70
Glass, 25 cl, returnable	29	15000	100	8500	57	78	70
Glass, 33 cl, disposable	33	15100	100	5000	34	67	70
PET, 50 cl, returnable	24	14700	98	3200	22	60	50
PET, 50 cl, disposable	28	15100	100	1600	11	56	50
PET, 150 cl, returnable	33	14800	99	2900	20	59	50
PET, 150 cl, disposable	33	13100	87	1200	8	48	50
Al & Steel cans, 33 cl	17	14500	97	1200	8	53	50
Al & Steel cans, 50 cl	14	14500	96	1300	9	53	50

5.2.2 Distribution of packaging and raw materials

Information on type of truck or cargo load for the packagings or their raw materials is not always given. Average figures for "black box" truck transport in Denmark (Danmarks Statistik, 1995) shows that inland freights usually are carried out with light or medium size trucks with an average cargo load utilisation of approx. 40% including empty returns. Export freights are carried out with heavy trucks with an average cargo load utilisation of approx. 70% including empty returns. It is likely that these figures are valid for Europe too.

The above scenario is used in case the truck is utilised on other tasks on the return trip and then the distance one way should be considered. In case of freight of heavy goods specifically for one company, full weight one way and empty return has been assumed.

5.3 Fuel consumption

Volvo has provided data on fuel consumption of various size of trucks (de Val 1992), updated by Rydberg (1997). The information is provided in table 5.5 together with verification against CORINAIR (1996).

Table 5.5
Truck fuel consumption by Volvo (de Val 1992, Rydberg 1997) and CORINAIR (1996).

Type	Load	Weight Total 1000 kg	Cargo 1000 kg	Driving mode	Fuel l/10km	Fuel MJ/km	Corinair category	Fuel, Corinair MJ/km Average load
Light, *e.g.* FL6	full	14	8.5	Urban	3.1	11.2	3.5-16t	9.7
	empty	5.5	0	Urban	2.2	7.9	urban	
Medium, *e.g.* FL10	full	24	14	Rural	3.9	14	>16t	14
	empty	10	0	Rural	2.9	10.4	rural	
Heavy, *e.g.* FL14, 16 incl. trailer	full	40	25	Highway	3.55	12.8	>16t	12.5
	empty	15	0	Highway	2.5	9	highway	
Heavy incl. trailer, Scandinavia	full	52	32	Highway	4.55	16.4	>16t	12.5
	empty	20	0	Highway	2.8	10.1	highway	

Table 5.5 show satisfying correlation between the CORINAIR size category 3.5-16 tons and Volvo's light truck and between CORINAIRS size category >16 tons and Volvos medium size and heavy trucks. Therefore CORINAIR emission factors are applied respectively, see section 5.4.

Volvo has not provided fuel consumption for all driving modes of each truck and the fuel consumption is therefore adjusted with factors obtained from CORINAIR, see table 5.6. These factors are verified with information from Eriksson *et al.* (1995) showing satisfying correlation considering that Eriksson *et al.* (1995) have more classifications of driving modes and reflects Swedish conditions.

Table 5.6
Relative fuel consumption calculated from CORINAIR (1996).

Truck size	Driving mode	Fuel consumption, CORINAIR * g/km	MJ/km	Relative fuel consumption	
3.5-16t	Urban	227	9.7	1	
	Rural	189	8	0.83	
	Highway	154	6.5	0.68	
>16t	Urban	366	15.6	1.12	1.24
	Rural	328	14	1	1.12
	Highway	294	12.5	0.9	1

* Heating value of diesel oil 42.7 MJ/kg

As a fair approximation, Volvo assumes that the fuel consumption is directly proportional to the cargo load of the truck (Rydberg 1997). From table 5.5, the fuel consumption at empty load is approx. 62-74 % of the fuel consumption at full load. This is a high proportion and implies that it may be reasonable without adding much uncertainty to simplify the work by grouping the fuel consumption into classes of cargo loads. This has been done in table 5.7. The classes are chosen from table 5.4. The fuel consumption is calculated from the figures in table 5.5 assuming the above mentioned linear relationship and adjusted with the factors in table 5.6.

Table 5.7 below presents general transport data. All the data has not been necessary for this study.

Table 5.7

Fuel consumption for trucks at different loads and driving modes.

Type of truck	Load	Load, ton	Traffic mode	Fuel consumption *		Correction **	Fuel consumption, corrected	
				l/100 km	MJ/km		MJ/km	MJ/kgkm
Light truck	Full	8.5	Urban	31	11.16	1	11.16	0.00131
e.g. Volvo FL6		8.5	Rural			0.83	9.26	0.00109
approx. 14 ton total		8.5	Highway			0.68	7.59	0.00089
	40%	3.4	Urban	25.6	9.22	1	9.22	0.00271
		3.4	Rural			0.83	7.65	0.00225
		3.4	Highway			0.68	6.27	0.00184
	Empty	0.0	Urban	22	7.92	1	7.92	-
		0.0	Rural			0.83	6.57	-
		0.0	Highway			0.68	5.39	-
Medium sized truck	Full	14.0	Urban			1.12	15.72	0.00112
e.g. Volvo FL10		14.0	Rural	39	14.04	1	14.04	0.00100
approx. 24 ton total		14.0	Highway			0.9	12.64	0.00090
	70%	9.8	Urban			1.12	14.52	0.00148
		9.8	Rural	36	12.96	1	12.96	0.00132
		9.8	Highway			0.9	11.66	0.00119
	50%	7.0	Urban			1.12	13.71	0.00196
		7.0	Rural	34	12.24	1	12.24	0.00175
		7.0	Highway			0.9	11.02	0.00157
	40%	5.6	Urban			1.12	13.31	0.00238
		5.6	Rural	33	11.88	1	11.88	0.00212
		5.6	Highway			0.9	10.69	0.00191
	Empty	0.0	Urban			1.12	11.69	-
		0.0	Rural	29	10.44	1	10.44	-
		0.0	Highway			0.9	9.40	-
Heavy truck	Full	25.0	Urban			1.24	15.85	0.00063
e.g. Volvo 14 & 16		25.0	Rural			1.12	14.31	0.00057
approx. 40 ton total		25.0	Highway	35.5	12.78	1	12.78	0.00051
	70%	17.5	Urban			1.24	14.44	0.00083
		17.5	Rural			1.12	13.04	0.00075
		17.5	Highway	32.4	11.65	1	11.65	0.00067
	50%	12.5	Urban			1.24	13.50	0.00108
		12.5	Rural			1.12	12.20	0.00098
		12.5	Highway	30.3	10.89	1	10.89	0.00087
	Empty	0.0	Urban			1.24	11.16	-
		0.0	Rural			1.12	10.08	-
		0.0	Highway	25	9.00	1	9.00	-
Heavy truck	Full	32.0	Urban			1.24	20.31	0.00063
e.g. Volvo 12 & 16		32.0	Rural			1.12	18.35	0.00057
approx. 52 ton total		32.0	Highway	45.5	16.38	1	16.38	0.00051
	70%	22.4	Urban			1.24	17.97	0.00080
		22.4	Rural			1.12	16.23	0.00072
		22.4	Highway	40.25	14.49	1	14.49	0.00065
	50%	16.0	Urban			1.24	16.41	0.00103
		16.0	Rural			1.12	14.82	0.00093
		16.0	Highway	36.75	13.23	1	13.23	0.00083
	Empty	0.0	Urban			1.24	12.50	-
		0.0	Rural			1.12	11.29	-
		0.0	Highway	28	10.08	1	10.08	-

* Fuel consumption full and empty supplied by Volvo

** CORINAIR (1996)

5.4 Emissions

In the following, the unit for the emissions is grams per MJ of fuel (g/MJ). The low heating value 42.95 MJ/kg has been used. For practical reasons the emissions are dealt with as fuel compounds (CO_2, SO_2), trace metals, and other emissions (particles, CO, VOC, NO_x, N_2O, NH_3).

CO_2

The CO_2 emission is 3138 g/kg calculated from the carbon amount in the fuel (CORINAIR 1996). This amount should be corrected for the amount of fuel which is only partly combusted - *i.e.* combusted into particles, CO and VOC. Referring to equations given by CORINAIR (1996) the CO_2 emission will be a few grams less and 3135 g/kg = 73.0 g/MJ CO_2 is then used as an appropriate value.

SO_2

The SO_2 emission is calculated from the sulphur content in the fuel. Using the legal limit value 0.05% S the SO_2 emission becomes 1g/kg = 0.0233 g/MJ.

Trace metals

The amount of heavy metals in fuels are published in CORINAIR (1996) and provided in table 5.8. By the combustion, the metals are released and emitted. The values are rather uncertain (an order of magnitude).

Table 5.8
Emission of heavy metals.

	mg/kg fuel	g/MJ
Cd	0.01	2.3E-07
Cu	1.7	4.0E-05
Cr	0.05	1.2E-06
Ni	0.07	1.6E-06
Se	0.01	2.3E-07
Zn	1	2.3E-05

Other emissions

For other emissions, CORINAIR (1996) have been used as reference. The data are the result of test cycle measurements simulating urban, rural and highway traffic. Unfortunately the data are representative of the technology from late eighties fulfilling the so called "EU 0" emission standard regarding CO, VOC and NO_x. Today's trucks fulfil the newer EU 1 norm adopted in 1993 and some trucks even fulfil the EU 2 standard adopted in 1997. The CORINAR data are therefore updated as described in the text below and provided in table 5.10. The new standards furthermore regulate particle emission.

CORINAIR use g/kg fuel as a unit and the emission standards uses g/kWh power delivered from the engine. For conversion between CORINAIR and the standards the fuel consumption 254 g/kWh is used (CORINAIR 1996). This fuel consumption corresponds to an efficiency of 33% of the engine, which is a likely - maybe somewhat conservative - average efficiency for a truck diesel engine.

The CORINAIR data show no or very small variation of particle and NO_x emission for urban, rural and highway driving and the EU 0 standard is met. The CO and VOC emission was remarkably larger by urban driving than for rural and highway driving. Actually, the EU 0 standard could not be fulfilled by urban driving which may happen because the emission standards are defined according to a standard test cycle (ECE R15) which do not aim at simulating practical driving modes.

It is assumed that the CO and VOC emissions are reduced according to the reductions in the new standards due to more precise dosing of the fuel, see table 5.9. Referring to CORINAIR, approx. 4% of the VOC is CH_4, which is accounted for. NO_x is assumed just to meet the new standards since NO_x is difficult to control on diesel engines as long as the catalyst is uncommon. The particle emission was not limited by the EU 0 standard and is assumed just to meet the new standards. The updated additional emissions are verified showing satisfying correlation with data from simulated test performed by Volvo and presented in Eriksson *et al.* (1995).

Besides the emissions described above, table 5.10 also shows N_2O and NH_3 emissions. The CH_4, N_2O and NH_3 emissions are converted from the unit g/km in CORINAIR to g/MJ using the fuel consumption in table 5.6.

Table 5.9
Emission reductions by standards.

Emission	EU0 g/kWh	EU1 g/kWh	EU0/EU1	EU2 g/kWh	EU0/EU2
Particles	-	0.36	-	0.15	-
CO	11.2	4.5	0.4	4	0.36
VOC	2.4	1.1	0.46	1.1	0.46
NO_x	14.4	8	(0.56)*	7	(0.49)*

* See text.

Table 5.10

Updated emissions from trucks, see text.

Emission	Unit	Update to EU1/EU2	Data source	Truck size and driving mode					
				3.5-16 t			>16 t		
				Urban	Rural	Highway	Urban	Rural	Highway
Particles	g/kg	-	CORINAIR	4.3	4.3	4.3	4.3	4.3	4.3
	g/kWh	-	calculated	1.09	1.09	1.09	1.09	1.09	1.09
	g/kWh	EU 1	standard	0.36	0.36	0.36	0.36	0.36	0.36
	g/kWh	EU 2	standard	0.15	0.15	0.15	0.15	0.15	0.15
	g/MJ	**EU 1**	**calculated**	**0.033**	**0.033**	**0.033**	**0.033**	**0.033**	**0.033**
	g/MJ	**EU 2**	**calculated**	**0.014**	**0.014**	**0.014**	**0.014**	**0.014**	**0.014**
CO	g/kg	-	CORINAIR	82.8	38.6	27.1	51.4	22.2	14.2
	g/kWh	-	calculated	21	9.8	6.7	13	5.6	3.6
	g/kWh	EU 1	standard	8.4	3.92	2.68	5.2	2.24	1.44
	g/kWh	EU 2	standard	7.5	3.5	2.39	4.64	2	1.29
	g/MJ	**EU 1**	**calculated**	**0.77**	**0.36**	**0.25**	**0.48**	**0.21**	**0.13**
	g/MJ	**EU 2**	**calculated**	**0.69**	**0.32**	**0.22**	**0.43**	**0.18**	**0.12**
VOC	g/kg	-	CORINAIR	12	4	4	16	8	8
	g/kWh	-	calculated	3	1	1	4.1	2	2
	g/kWh	EU 1, 2	standard	1.38	0.46	0.46	1.89	0.92	0.92
NMVOC	**g/MJ**	**EU 1, 2**	**calculated**	**0.122**	**0.04**	**0.04**	**0.166**	**0.081**	**0.081**
NOx	g/kg	-	CORINAIR	38.5	39.1	38.9	44.2	45.2	45.8
	g/kWh	-	calculated	9.8	9.9	[illegible]	11.2	11.5	11.6
	g/kWh	EU 1	standard	8	8	[illegible]	8	8	8
	g/kWh	EU 2	standard	7	7	[illegible]	7	7	7
	g/MJ	**EU 1**	**calculated**	**0.73**	**0.73**	**0.73**	**0.73**	**0.73**	**0.73**
	g/MJ	**EU 2**	**calculated**	**0.64**	**0.64**	**0.64**	**0.64**	**0.64**	**0.64**
CH4	g/km	-	CORINAIR	0.085	0.023	0.02	0.175	0.08	0.07
	g/MJ	**EU 1, 2**	**calculated**	**0.0051**	**0.0017**	**0.0017**	**0.0069**	**0.0034**	**0.0034**
N2O	g/km	-	CORINAIR	0.03	0.03	0.03	0.03	0.03	0.03
	g/MJ	**-**	**calculated**	**0.0031**	**0.0037**	**0.0045**	**0.0019**	**0.0021**	**0.0024**
NH_3	g/km	-	CORINAIR	0.003	0.003	0.003	0.003	0.003	0.003
	g/MJ	**-**	**calculated**	**0.00031**	**0.00037**	**0.00045**	**0.00019**	**0.00021**	**0.00024**

The complete lists of emission factors (including heavy metals, CO_2 and SO_2) are presented in annex A. In table 5.10 the emission factors were calculated for general purposes. Only medium and heavy trucks (>16 t) were relevant in this study.

In annex A, which is a printout from the energy database of the LCAiT program, the emissions are presented per MJ of diesel for the three driving modes urban, rural and highway.

6 Transport in private car

The significance of switching between packaging types for the fuel consumption of private cars on shopping trips is estimated below.

Fuel consumption and weight of a car has been investigated by *e.g.*:

Schäper and Leitermann (1996):
Assumes 0.5 l or 0.63 l gasoline per 100 kg weight per 100 km. The assumption seems based on few measurements and the closer circumstances are not explained.

Audi (1997):
Assumes 0.6 l gasoline per 100 kg weight per 100 km. The assumption is not documented.

Wallentowitz *et al.* (1996):
Assumes 0.37 l gasoline per 100 kg weight per 100 km urban driving and 0.1 - 0.2 l gasoline per 100 kg weight per 100 km on highway. The assumptions are based on measurements on four types of cars in different driving cycles and seem well documented. Also the weight difference is for the same type of car and not for different cars of different weight.

Klöckner (1996):
Provide an example showing 1 l gasoline per 100 kg weight per 100 km for urban traffic and 0.46 l gasoline per 100 kg weight per 100 km on highway. However, this example is for different types of cars with different weight, and other fuel consuming factors than weight is then included as *e.g.* air resistance and engine efficiency.

Based on the above references the value 0.4 l = 0.3 kg gasoline per 100 kg weight per 100 km urban driving is chosen in this study being close to Wallentowitz´ value as the most reliable. The amount is equal to 0.00003 kg gasoline/kgkm.

The largest weight of packaging is for the 33 cl glass bottle, 909 litres per functional unit (3030 bottles). If say, as a rough estimate, the bottles are transported 10 km by car, the energy needed is 0.00003 kg/kgkm * 909 kg * 10 km = 0.27 kg gasoline = 11.5 MJ direct energy. This amount is negligible compared to the total energy of the functional unit (roughly 5000 MJ).

7 Other transports

Fuel consumption

The fuel consumption for ships and trains (presented in table 7.1) are based on Kildé (1995). The electricity consumption for trains was found in Tillman *et al.* 1991.

Table 7.1
Fuel consumption for other transports.

Other transports	Fuel	Fuel consumption [MJ/ton km]
Ship, bulk carrier	Fuel oil, ship (2-stroke)	0.050
Ship, coaster	Diesel, ship (4-stroke)	0.340
Ship, container	Fuel oil, ship (2-stroke)	0.300
Train, diesel	Diesel, train	0.720
Train, electricity	Electricity	0.300

Emissions

Data for emissions from ships, diesel trains, LPG engines and others have been obtained from CORINAIR (1996). The data, which are based on measurements, are given in table 7.2. For metal emissions, the data in table 5.8 are used, except for LPG engines, which are not expected to give any heavy metal emissions. The emissions have been recalculated using the low calorific values: diesel oil (42.95 MJ/kg), ship fuel oil (41 MJ/kg) and LPG (46 MJ/kg).

Table 7.2
Emissions for other transports.

Emission	Unit	Data source	Transport or other media: Diesel, train	Fuel oil, ship (2-stroke)	Diesel, ship (4-stroke)	LPG, forklift
CO2	g/kg	Corinair	3135	3170	3170	3030
	g/MJ	**calculated**	**73**	**77.3**	**73.8**	**65.9**
SO2*	g/kg	calculated	1	60	2	0
	g/MJ	**calculated**	**0.0233**	**1.46**	**0.0466**	**0**
Particles	g/kg	Corinair	4.58	4.48	4.48	0
	g/kWh	Corinair	-	-	-	0
	g/MJ	**calculated**	**0.107**	**0.109**	**0.107**	**0**
CO	g/kg	Corinair	10.7	7.4	7.4	-
	g/kWh	Corinair	-	1.6	1.6	15
	g/MJ	**calculated**	**0.249**	**0.18**	**0.172**	**0.93**
NMVOC	g/kg	Corinair	4.65	2.3	2.3	-
	g/kWh	Corinair	-	0.5	0.5	13.5
	g/MJ	**calculated**	**0.108**	**0.056**	**0.0536**	**0.84**
NOx	g/kg	Corinair	39.6	87	57	-
	g/kWh	Corinair	-	17	12	10
	g/MJ	**calculated**	**0.922**	**2.1**	**1.33**	**0.62**
CH4	g/kg	Corinair	0.18	0.1	0.1	-
	g/kWh	Corinair	-	-	-	1
	g/MJ	**calculated**	**0.0042**	**0.0024**	**0.0023**	**0.062**
N2O	g/kg	Corinair	1.24	0.2	0.2	-
	g/kWh	Corinair	-	0.04	0.04	0.05
	g/MJ	**calculated**	**0.029**	**0.005**	**0.0047**	**0.0031**
NH_3	g/kg	Corinair	0.007	-	-	-
	g/kWh	Corinair	-	-	-	0.003
	g/MJ	**calculated**	**0.00016**	-	-	**0.00019**

* S content in oil: 0% for LPG, 3% for 2-stroke ships; 0.1 % for 4-stroke ships and 0.05% for others.

8 Data quality assessment

In energy and transport systems, the main environmental impacts are due to fuel combustion. The uncertainties will be dominated by the uncertainties on the fuel combustion.

Since CO_2 emissions are based on statistical information on carbon contents related to calorific value, these data are precise within a few percent, for coal maybe somewhat higher.

The SO_2, NO_x and particle emissions from power plants and transportation are based on emission limits and may thus be regarded as a slight overestimate, as the actual values may be approximately 20% below the emission limits in order to ensure compliance. For power plants, the emissions are in relation to the amount of exhaust gas, which can only be determined with a precision around 15%.

Data from Frischknecht et al. (1994, 1996) are the best available, but the uncertainty of these data is difficult to determine. The main uncertainty is expected to arise from differences in representativeness, as emissions vary much depending on fuel origin and plant characteristics. Estimated uncertainties of 50% on CO and VOC's and 100% for other emissions may be applied for sensitivity analysis. For heavy metals, even larger uncertainties are likely as heavy metal contents vary very much between fuels depending on origin as e.g. for Hg and Sr.

For the average European electricity scenario, many uncertainties occur when combining different statistical data. However, many of the uncertainties are likely to even out each other in the aggregation, and the underlying statistical information is very precise. Thus, the aggregated uncertainty on the fuel mix is below 2 percent.

The uncertainties on the emissions reported by CORINAIR and Eurostat are likely to be in the same order of magnitude as those reported above for Frischknecht et al. (1994, 1996).

Data for waste incineration is based on statistical data and typical calorific values of the materials. The aggregated uncertainty of these values is around 10%.

The aggregated uncertainty on the distribution scenarios is less than 10%. The uncertainties on the emissions are in the same ranges as for power plants (see above).

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Annex A:

Emission factors for energy production and transports

The emission factors in this annex is presented by a print-out from the LCA software *LCA inventory Tool (LCAiT)*. In this software each energy source is called "Energy carrier". The environmental load associated with combustion of a fuel is presented under "Emissions etc at final use" and the pre-combustion is presented under "Emisssions etc at extraction". Some parameters appear in both of the two categories air- and water emissions. To be able to separate these parameters, the emissions to water have been given the name: parameter (aq) e.g. Cu (aq). Resources have in the same way been called resource (r) e.g. crude oil (r). Non-elementary inflows have been given the name parameter (in). The units in LCAiT is limited to grams for emissions etc and MJ for energy. For parameters measured in other units than gram, the unit has been added to the parameter name e.g. Radioactive emissions [kBq].

The energy carriers in this annex is summarised in table A.1.

Table A.1
Energy carriers (fuels) in this annex.

Energy carrier (fuel)	Fuel type
Bark	Fuel
Diesel, heavy & medium truck (highway)	Transport fuel
Diesel, heavy & medium truck (rural)	Transport fuel
Diesel, heavy & medium truck (urban)	Transport fuel
Diesel, ship (4-stroke)	Transport fuel
Diesel, train	Transport fuel
Fuel oil, ship (2-stroke)	Transport fuel
Hard coal	Fuel
LPG, forklift	Transport fuel
LPG, thermal	Fuel
Natural gas (<100kW)	Fuel
Natural gas (>100kW)	Fuel
Oil, heavy fuel	Fuel
Oil, light fuel	Fuel
Peat	Fuel

Energy Carrier Bark

Emissions etc at final use	**[g/MJ]**
Waste, slags & ashes	3.600
SO2	1.50e-002
NOx	0.140
CO	0.563
Particulates	0.116

Emissions etc at extraction	**[g/MJ]**
Bark (in)	58.800

Energy type Renewable fuel

Notes
Site specific data for combustion in a Swedish paper mill (Hylte Bruk) have been used (section 4.6).

The environmental load for the extraction of bark is not included in the study (section 2.4). Bark has therefore been accounted for as a non-elementary inflow.

Energy Carrier Diesel, heavy & medium truck (highway)

Emissions etc at final use	**[g/MJ]**
Cd	2.30e-007
Cu	4.00e-005
Ni	1.60e-006
Se	2.30e-007
Zn	2.30e-005
Particulates	3.30e-002
CO	0.130
CO2	73.000
NOx	0.730
CH4	3.40e-003
NMVOC, diesel engines	8.10e-002
SO2	2.33e-002
N2O	2.40e-003
NH3	2.40e-004
Cr	1.20e-006

Emissions etc at extraction	**[g/MJ]**
CO2	10.808
CO	1.70e-002
NOx	6.75e-002
SO2	7.03e-002
NMVOC	0.204
CH4	0.102
Dioxin	8.78e-011
NH3	8.50e-006
N2O	1.86e-004
HCl	2.47e-004
H2S	4.88e-006
HF	2.65e-005
Particulates	4.19e-002
Radioactive emissions [kBq]	2.65e+003
As	4.59e-007
Cd	9.00e-007
Cr	8.86e-007
Hg	1.10e-007
Ni	4.22e-005
Pb	3.68e-006
CN-	7.10e-009
COD (aq)	3.85e-003
BOD-5 (aq)	1.17e-004
Tot-N (aq)	5.63e-003
Phosphate (aq)	6.18e-005
H2S (aq)	2.03e-007
Oil (aq)	2.38e-002
Organics (aq)	1.99e-002
Radioactive emissions [kBq] (aq)	24.900
Al (aq)	8.07e-004
As (aq)	2.63e-006
Cd (aq)	1.46e-006
Co (aq)	1.58e-006
Cr (aq)	1.95e-005
Cu (aq)	6.41e-006
Ni (aq)	7.90e-006
Pb (aq)	1.02e-005

--- To be continued ---

Sb (aq)	2.22e-008
Sn (aq)	1.74e-003
V (aq)	5.20e-006
Zn (aq)	2.19e-005
F- (aq)	2.94e-005
Cl- (aq)	0.697
SO42- (aq)	2.75e-002
CN- (aq)	6.20e-006
Waste, industrial	2.992
Waste, hazardous	3.05e-002
Waste, highly radioactive	8.75e-002
Crude oil (r)	25.728
Natural gas (r)	1.063
Hard coal (r)	0.495
Brown coal (r)	0.412
Wood (r)	2.53e-002
Uranium (as pure U) (r)	3.00e-005
Hydro power-water (r)	280.000

Energy type Fossil fuel

Notes
Emission factors for heavy and medium trucks - highway driving - have been calculated mainly based on CORINAIR 1996 (section 5.4).

The pre-combustion emissions were found in Frischknecht et al. 1994 (section 2.2).

Energy Carrier Diesel, heavy & medium truck (rural)

Emissions etc at final use	**[g/MJ]**
CO2	73.040
CO	0.210
NOx	0.730
SO2	2.33e-002
N2O	2.10e-003
NH3	2.10e-004
NMVOC, diesel engines	8.10e-002
CH4	3.40e-003
Particulates	3.30e-002
Zn	2.30e-005
Se	2.30e-007
Ni	1.60e-006
Cu	4.00e-005
Cd	2.30e-007
Cr	1.20e-006

Energy type Fossil fuel

Notes
Emission factors for heavy and medium trucks - rural driving - have been calculated mainly based on CORINAIR 1996 (section 5.4).

The pre-combustion emissions are the same as for "Diesel, heavy & medium truck (highway)".

Energy Carrier Diesel, heavy & medium truck (urban)

Emissions etc at final use	**[g/MJ]**
CO2	73.040
CO	0.480
NOx	0.730
SO2	2.33e-002
NH3	1.90e-004
N2O	1.90e-003
NMVOC, diesel engines	0.170
CH4	6.90e-003
Particulates	3.30e-002
Zn	2.30e-005
Se	2.30e-007
Ni	1.60e-006
Cu	4.00e-005
Cd	2.30e-007
Cr	1.20e-006

Energy type Fossil fuel

Notes
Emission factors for heavy and medium trucks - urban driving - have been calculated mainly based on CORINAIR 1996 (section 5.4).

The pre-combustion emissions are the same as for "Diesel, heavy & medium truck (highway)".

--- To be continued ---

Energy Carrier Diesel, ship (4-stroke)

Emissions etc at final use	[g/MJ]
Cr	1.20e-006
Cd	2.30e-007
Cu	4.00e-005
Ni	1.60e-006
Se	2.30e-007
Zn	2.30e-005
Particulates	0.107
NMVOC, diesel engines	5.60e-002
N2O	4.70e-003
SO2	4.66e-002
NOx	1.330
CO	0.172
CO2	73.800

Energy type Fossil fuel

Notes
Emission factors for 4-stroke diesel ships are based on CORINAIR 1996 (chapter 7).

The pre-combustion emissions are the same as for "Diesel, heavy & medium truck (highway)".

Energy Carrier Diesel, train

Emissions etc at final use	[g/MJ]
Cr	1.20e-006
Cd	2.30e-007
Cu	4.00e-005
Ni	1.60e-006
Se	2.30e-007
Zn	2.30e-005
Particulates	0.107
CH4	4.20e-003
NMVOC, diesel engines	0.108
NH3	1.60e-004
N2O	2.90e-002
SO2	2.33e-002
NOx	0.922
CO	0.249
CO2	73.040

Energy type Fossil fuel

Notes
Emission factors for diesel trains are based on CORINAIR 1996 (chapter 7).

The pre-combustion emissions are the same as for "Diesel, heavy & medium truck (highway)".

Energy Carrier Fuel oil, ship (2-stroke)

Emissions etc at final use	[g/MJ]
Cr	1.20e-006
Cd	2.40e-007
Cu	4.10e-005
Ni	1.70e-006
Se	2.40e-007
Zn	2.40e-005
Particulates	0.109
NMVOC, diesel engines	5.85e-002
N2O	5.00e-003
SO2	1.460
NOx	2.100
CO	0.180
CO2	77.300

Emissions etc at extraction	[g/MJ]
Organics (aq)	2.05e-002
Oil (aq)	2.67e-002
PO43- (aq)	8.00e-005
Tot-N (aq)	2.97e-003
CN-	7.90e-006
Pb	5.23e-006
Ni	5.98e-005
Hg	1.76e-007
Cr3+	1.33e-006
Cd	1.61e-006

--- To be continued ---

As	7.86e-007
Radioactive emissions [kBq]	4.030
Particulates	4.47e-002
HF	4.20e-004
H2S	5.90e-006
HCl	3.94e-004
N2O	2.32e-004
NH3	1.10e-005
Dioxin	1.17e-010
Benzene	7.89e-004
CH4	0.116
NMVOC, oil combustion	0.231
SO2	9.75e-002
NOx	8.03e-002
CO	1.89e-002
CO2	15.000
Hydro power-water (r)	408.000
Uranium (as pure U) (r)	5.00e-005
Biomass (r)	3.06e-002
Brown coal (r)	0.641
Hard coal (r)	0.678
Natural gas (r)	1.240
Crude oil (r)	29.100
Waste, radioactive	1.40e-004
Waste, hazardous	3.00e-002
Waste, industrial	3.000
SO42- (aq)	3.06e-002
Cl- (aq)	0.788
F- (aq)	3.30e-004
Pb (aq)	1.20e-005
Ni (aq)	9.85e-006
Cr3+ (aq)	2.39e-005
Cd (aq)	1.60e-006
As (aq)	3.30e-006
Radioactive emissions [kBq] (aq)	3.77e-002

Energy type Fossil fuel

Notes
Emission factors for 2-stroke fuel oil ships are based on CORINAIR 1996 (chapter 7).

The pre-combustion emissions were found in Frischknecht et al. 1994 (section 2.2).

Energy Carrier Hard coal

Emissions etc at final use	[g/MJ]
Pb	2.66e-004
CO2	91.500
CO	0.100
NOx	0.200
SO2	0.500
VOC	1.72e-003
CH4	1.00e-002
Ethane	1.50e-003
Propane	1.00e-003
Alkanes	5.00e-004
Ethene	3.00e-003
Acetylene	5.00e-004
Propene	5.00e-004
Alkenes	5.00e-004
Benzene	5.00e-004
Toluene	1.00e-004
Xylene	1.00e-004
Benzo(a)pyrene	1.00e-008
Dioxin	2.00e-011
Formaldehyde	8.00e-005
N2O	1.00e-003
HCl	5.00e-002
HF	1.80e-003
Particulates	5.00e-002
Mn	3.79e-004
Co	1.07e-004
Cr	4.14e-004
Cu	3.38e-004
Hg	2.00e-006

--- To be continued ---

As	5.90e-005
Be	7.00e-006
Cd	1.70e-005
Ni	5.00e-004
Mo	8.60e-005
Sb	4.80e-005
Se	3.80e-005
V	3.34e-004
Zn	3.93e-004
Emissions etc at extraction	[g/MJ]
N2O	5.48e-005
NH3	3.88e-006
Aldehydes	1.27e-006
Dioxin	5.80e-017
Aromates (C9-C10)	1.80e-005
Benzo(a)pyrene	1.41e-009
PAH	2.53e-009
CO2	4.742
CH4	0.495
HC	5.22e-003
NMVOC, petrol engines	3.21e-013
NMVOC, diesel engines	2.22e-003
NMVOC, power plants	9.09e-004
VOC, diesel engines	1.19e-003
VOC, coal combustion	5.07e-005
VOC, natural gas combustion	3.36e-012
SO2	4.14e-002
NOx	6.22e-002
CO	1.01e-002
HCl	3.11e-004
Organics	2.53e-006
Particulates	4.25e-003
Radioactive emissions [kBq]	3.321
As	2.53e-008
Cd	2.53e-009
Cr	1.27e-008
Cu	2.53e-008
Hg	1.03e-007
Ni	1.90e-008
Pb	2.53e-008
Se	1.01e-008
V	3.80e-008
Zn	1.27e-007
Metals	8.18e-007
COD (aq)	8.18e-006
BOD (aq)	4.09e-006
Dissolved organics (aq)	2.25e-013
Dissolved solids (aq)	3.41e-002
Suspended solids (aq)	5.61e-004
NO3-N (aq)	2.11e-007
NH4-N (aq)	2.73e-005
Nitrogen (aq)	1.24e-005
H+ (aq)	2.45e-005
HC (aq)	1.64e-005
Oil (aq)	9.22e-005
Phenol (aq)	5.62e-015
Aromates (C9-C10) (aq)	5.62e-006
Radioactive emissions [kBq] (aq)	5.50e-002
Al (aq)	3.41e-005
Fe (aq)	6.83e-005
Mn (aq)	3.41e-005
Ni (aq)	3.41e-006
Sr (aq)	1.71e-004
Zn (aq)	1.06e-005
Metals (aq)	4.09e-006
F- (aq)	1.02e-004
Cl- (aq)	0.589
SO42- (aq)	2.41e-002
Salt (aq)	3.41e-003
Waste, industrial	0.163
Waste, mineral	1.78e-003
Waste, slags & ashes (waste incin.)	2.67e-007
Waste, slags & ashes (energy prod.)	0.100

--- To be continued ---

Waste, bulky	18.500
Waste, sludge	1.44e-011
Waste, rubber	2.09e-005
Waste, chemical	1.38e-004
Waste, hazardous	0.609
Waste, radioactive	1.07e-004
Crude oil, feedstock (r)	5.80e-006
Crude oil (r)	0.944
Natural gas (r)	5.24e-002
Hard coal (r)	57.550
Brown coal (r)	0.526
Softwood (r)	1.79e-002
Biomass (r)	3.30e-010
Fuel, unspecified [MJ] (r)	1.91e-007
Uranium (as pure U) (r)	3.57e-005
Hydro power-water (r)	1.013
NaCl (r)	1.15e-004
Clay (r)	2.45e-005
CaCO3 (r)	1.15e-004
Al (r)	6.54e-005
Fe (r)	6.86e-005
Mn (r)	4.05e-007
Water (r)	1.23e+004
Ground water (r)	1.55e-006
Surface water (r)	3.16e-008

Energy type Fossil fuel

Notes
Emission factors for combustion of hard coal are based on Frischknecht et al. 1996 (section 4.2).

The pre-combustion emissions were found in Frischknecht et al. 1994 (section 2.1).

Energy Carrier LPG, forklift

Emissions etc at final use	**[g/MJ]**
NMVOC, natural gas combustion	0.840
CH4	6.20e-002
NH3	1.90e-004
N2O	3.10e-003
NOx	0.620
CO	0.930
CO2	65.870

Emissions etc at extraction	**[g/MJ]**
Hydro power-water (r)	408.000
Uranium (as pure U) (r)	5.00e-005
Biomass (r)	3.06e-002
Brown coal (r)	0.641
Hard coal (r)	0.678
Natural gas (r)	1.240
Crude oil (r)	29.100
Waste, radioactive	1.40e-004
Waste, hazardous	3.00e-002
Waste, industrial	3.000
SO42- (aq)	3.06e-002
Cl- (aq)	0.788
F- (aq)	3.30e-004
Pb (aq)	1.20e-005
Ni (aq)	9.85e-006
Cr3+ (aq)	2 39e-005
Cd (aq)	1.60e-006
As (aq)	3.30e-006
Radioactive emissions [kBq] (aq)	3.77e-002
Organics (aq)	2.05e-002
Oil (aq)	2.67e-002
PO43- (aq)	8.00e-005
Tot-N (aq)	2.97e-003
CN-	7.90e-006
Pb	5.23e-006
Ni	5.98e-005
Hg	1.76e-007
Cr3+	1.33e-006
Cd	1.61e-006
As	7.86e-007
Radioactive emissions [kBq]	4.030

--- To be continued ---

Particulates	4.47e-002
HF	4.20e-004
H2S	5.90e-006
HCl	3.94e-004
N2O	2.32e-004
NH3	1.10e-005
Dioxin	1.17e-010
Benzene	7.89e-004
CH4	0.116
NMVOC, oil combustion	0.231
SO2	9.75e-002
NOx	8.03e-002
CO	1.89e-002
CO2	15.000

Energy type Fossil fuel

Notes
Emission factors for LPG combustion in forklifts are based on CORINAIR 1996 (chapter 7).

The pre-combustion emissions were found in Frischknecht et al. 1994 (section 2.2).

Energy Carrier LPG, thermal

Emissions etc at final use	[g/MJ]
CO2	65.000
CO	4.00e-002
NOx	6.00e-002
N2O	3.00e-003
NH3	1.00e-005
NMVOC, natural gas combus...	3.50e-003
CH4	1.50e-003

Energy type Fossil

Notes
Emission factors for LPG combustion for the production of thermal energy are based on CORINAIR 1996 (section ...).

The pre-combustion emissions are the same as for "LPG, forklift".

Energy Carrier Natural gas (<100 kW)

Emissions etc at final use	[g/MJ]
Benzo(a)pyrene	1.00e-008
Toluene	2.00e-004
Benzene	4.00e-004
PAH	1.00e-005
Pentane	1.20e-003
Butane	7.00e-004
CO2	56.000
Propane	2.00e-004
CH4	2.00e-003
SO2	5.00e-004
NOx	3.00e-002
CO	2.00e-002
Formaldehyde	1.00e-004
Acetaldehyde	1.00e-006
N2O	5.00e-004
Particulates	1.00e-004
Hg	5.50e-008

Emissions etc at extraction	[g/MJ]
CO2	3.149
Natural gas (r)	20.700
Crude oil (r)	9.89e-002
Waste, industrial	54.300
Waste, hazardous	7.520
SO2	2.39e-004
NMVOC, natural gas combustion	1.70e-003
CH4	2.10e-003
N2O	4.68e-005
CO	3.44e-004
NOx	1.49e-002

Energy type Fossil fuel

Notes
Emission factors for combustion of natural gas are based on Frischknecht et al. 1996 (section 4.5).

--- To be continued ---

The pre-combustion emissions were found in Bakkane 1994 (section 2.3).

Energy Carrier Natural gas (>100 kW)

Emissions etc at final use	**[g/MJ]**
CO2	59.100
CO	1.40e-002
NOx	4.70e-002
SO2	5.00e-004
CH4	2.00e-003
Propane	2.00e-004
Butane	7.00e-004
Pentane	1.20e-003
PAH	1.00e-005
Benzene	4.00e-004
Toluene	2.00e-004
Benzo(a)pyrene	1.00e-008
Formaldehyde	1.00e-004
Acetaldehyde	1.00e-006
N2O	1.00e-004
Particulates	2.00e-004
Hg	5.50e-008

Energy type Fossil fuel

Notes
Emission factors for combustion of natural gas are based on Frischknecht et al. 1996 (section 4.5).

The pre-combustion emissions are the same as for "Natural gas (<100 kW)".

Energy Carrier Oil, heavy fuel

Emissions etc at final use	**[g/MJ]**
CO2	77.900
CO	1.50e-002
NOx	0.160
SO2	0.306
CH4	3.00e-003
Ethane	0.0
Propane	3.00e-005
Alkanes	6.00e-004
Ethene	0.0
Acetylene	0.0
Propene	0.0
Alkenes	3.00e-005
PAH	5.00e-007
Benzene	0.0
Toluene	3.00e-005
Benzo(a)pyrene	3.00e-008
Aromates (C9-C10)	1.50e-004
Formaldehyde	4.50e-004
Aldehydes	0.0
N2O	1.60e-003
HCl	1.44e-003
HF	1.44e-004
Particulates	2.90e-002
As	1.30e-005
Ca	8.00e-005
Cd	3.30e-005
Co	3.30e-005
Cr	1.60e-005
Cu	4.90e-005
Fe	1.80e-004
Hg	1.50e-007
Mo	1.60e-005
Na	7.50e-004
Ni	6.50e-004
Pb	5.70e-005
Se	1.20e-005
V	2.60e-003
Zn	4.00e-005
TOC (aq)	0.0

Energy type Fossil fuel

Notes

--- To be continued ---

Emission factors for combustion of heavy fuel oil are mainly based on Frischknecht et al. 1996 (section 4.3).

The pre-combustion emissions are the same as for "Fuel oil, ship (2-stroke)".

Energy Carrier Oil, light fuel

Emissions etc at final use	**[g/MJ]**
CO2	74.000
CO	5.00e-003
NOx	2.50e-002
SO2	2.35e-002
CH4	8.00e-004
Ethane	8.00e-005
Propane	1.20e-004
Alkanes	1.00e-003
Ethene	2.00e-004
Acetylene	4.00e-005
Propene	8.00e-005
Alkenes	8.00e-005
PAH	4.60e-007
Benzene	8.00e-005
Toluene	4.00e-005
Aromates (C9-C10)	8.00e-005
Formaldehyde	2.40e-005
Aldehydes	0.0
HCl	0.0
HF	4.50e-006
Particulates	1.00e-004
As	0.0
Ca	0.0
Cd	0.0
Co	0.0
Cr	0.0
Cu	4.00e-007
Fe	0.0
Hg	5.00e-007
Mo	0.0
Na	0.0
Pb	0.0
Se	0.0
V	0.0
Zn	5.00e-007
TOC (aq)	2.50e-004

Emissions etc at extraction	**[g/MJ]**
CO2	10.831
CO	1.70e-002
NOx	6.76e-002
SO2	7.04e-002
NMVOC	0.205
CH4	0.102
Dioxin	8.80e-011
NH3	8.50e-006
N2O	1.87e-004
HCl	2.47e-004
H2S	4.89e-006
HF	2.51e-005
Particulates	4.20e-002
Radioactive emissions [kBq]	2.66e+006
As	4.60e-007
Cd	9.03e-007
Cr	8.88e-007
Hg	1.10e-007
Ni	4.23e-005
Pb	3.69e-006
CN-	7.12e-009
COD (aq)	3.86e-003
BOD-5 (aq)	1.17e-004
Tot-N (aq)	5.64e-003
Phosphate (aq)	6.19e-005
H2S (aq)	2.04e-007
Oil (aq)	2.39e-002
Organics (aq)	1.99e-002
Radioactive emissions [kBq] (aq)	2.50e+004
Al (aq)	8.08e-004

--- To be continued ---

As (aq)	2.63e-006
Cd (aq)	1.47e-006
Co (aq)	1.59e-006
Cr (aq)	1.95e-005
Cu (aq)	6.42e-006
Ni (aq)	7.92e-006
Pb (aq)	1.02e-005
V (aq)	5.21e-006
Sb (aq)	2.22e-008
Sn (aq)	1.74e-003
Zn (aq)	2.20e-005
F- (aq)	2.95e-005
Cl- (aq)	0.698
SO42- (aq)	2.76e-002
CN- (aq)	6.21e-006
Waste, industrial	2.998
Waste, hazardous	3.06e-002
Waste, highly radioactive	8.75e-005
Crude oil (r)	25.789
Natural gas (r)	1.079
Hard coal (r)	0.496
Brown coal (r)	0.413
Wood (r)	2.53e-002
Uranium (as pure U) (r)	3.00e-005
Hydro power-water (r)	280.000

Energy type Fossil fuel

Notes
Emission factors for combustion of light fuel oil are mainly based on Frischknecht et al. 1996 (section 4.3).

The pre-combustion emissions were found in Frischknecht et al. 1994 (section 2.2).

Energy Carrier Peat

Emissions etc at final use	**[g/MJ]**
HC	6.00e-006
SO2	0.240
NOx	0.150
CO2	103.000
Particulates	0.177

Emissions etc at extraction	**[g/MJ]**
Peat (in)	47.600

Energy type Fossil fuel

Notes
Data for peat combustion were found in Christensen 1991 (section 4.6).

The environmental load for the extraction of peat is not included in the study (section 2.4). Peat has therefore been accounted for as a non-elementary inflow.

Calculation of emissions based on statistical information

Country	Production	CO2		SO2		NO2		Particles	CO		NMVOC	CH4	N2O
	GWh	1000t		1000t		1000t		1000t	1000t		1000t	1000t	1000t
		Corinair*	Eurostat	Corinair*	Eurostat	Corinair*	Eurostat	Eurostat**	Corinair*	Eurostat	Corinair	Corinair	Corinair
Belgium	68563	25839	26700	101,51	83	71,07	58	4	2,96	2	0,49	0,17	2,64
Denmark	37795	32840	33000	104,51	103	95,6	90	5	23	23	0,74	0,69	1,06
Germany	488613	316603	345400	1722,1	1876	429,05	488	173	107,71	105	6,35	6,39	11,49
Grækenland	37377	43592	39300	346,09	n.r.	72,37	n.r.	n.a.	6,28	n.a.	1,86	0,59	1,12
Spain (1993)	154289	66600	66600	2024	1939	272	253	n.r.	20,43	19	n.a.	n.a.	n.a.
France	454476	24861	27700	157,46	190	62,92	75	9	3,58	29	0,65	0,36	0,58
Ireland	16107	12381	12500	95,54	n.r.	45,12	n.r.	n.r.	3,43	n.r.	0,26	0	1,63
Italy (1992)	219871	118500	118500	662	608	399	362	n.r.	25,38	23	n.a.	n.a.	n.a.
Luxembourg	1150	1064	1200	0,11	n.r.	0,26	n.r.	n.a.	0,04	n.a.	0,005	0,002	0,004
Nederland	76507	40800	48900	20,5	16	58,7	60	1	3,47	13	0,39	0,44	0,73
Austria	51855	6958	11800	2,72	17	4,17	10	n.r.	0,42	9	0,08	0,05	0,06
Portugal	30191	15900	15900	160	150	55	51	n.r.	2,15	2	n.a.	n.a.	n.a.
Finland	62084	23027	25100	47	44	88	54	n.a.	11,45	7	n.a.	n.a.	n.a.
Sweden	138736	6674	9400	6,97	n.r.	7,19	n.r.	n.a.	3,11	n.r.	1,07	0,42	0,5
U.K.	306138	162436	173700	1764,3	1759	528,12	526	19	240,16	21	4,31	10,54	7,75
Total	2143752	898075	955700	7215	6785	2189	2027	211	454	253	16,21	19,65	27,56
96% allocation		862152		6926		2102		202,56	435		15,5568	18,86592	26,46144
GWh-n.a./n.r.		2143752		2143752		2143752		1432092	2143752		1677317	1677317	1677317
g per kWh		402,17		3,23		0,98		0,141	0,203		0,0093	0,0112	0,0158
g per MJ out		111,71		0,90		0,27		0,039	0,084		0,0026	0,0031	0,0044

n.a. = not available; n.r. = not relevant (data not representative e.g. due to age)

* For Spain, Italy, Portugal and Finland Corinair data was not available and the Eurostat data was used corrected as to autoproducers, see table 3.5 in the main text.

**The Danish value for particles is based on green accounts from Danish electricity producers.

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Life Cycle Assessment of Packaging Systems for Beer and Soft Drinks : Energy and Transport Scenarios

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Technical Report 7

Forfatter(e):
Frees, Niels; Weidema, Bo Pedersen

Udførende institution(er):
Chalmers Industriteknik; Instituttet for Produktudvikling

Resumé:
Rapporten er en del af en livscyklusvurdering, hvor potentielle miljøeffekter fra forskellige eksisterende og alternative emballagesystemer til øl og læskedrikke, påfyldt og solgt i Danmark, sammenlignes. Miljøvurderingen sammenligner retur- og engangsflasker af hhv. glas og PET samt aluminiums- og ståldåser. Denne delrapport handler om de anvendte energi- og transportscenarier.

Emneord:
livscyklusvurdering; emballage; drikkevarer; øl; transport; distribution; energi; forbrug

Andre oplysninger:
Hører sammen med en hovedrapport: Main Report (Miljøprojekt, 399) og 6 tekniske delrapporter om de enkelte emballagetyper: Refillable Glass Bottles (Miljøprojekt, 400), Disposable Glass Bottles (Miljøprojekt, 401), Aluminium Cans (Miljøprojekt, 402), Steel Cans (Miljøprojekt, 403), Refillable PET Bottles (Miljøprojekt, 404), Disposable PET Bottles (Miljøprojekt, 405). - Opdatering af: Miljømæssig kortlægning af emballager til øl og læskedrikke (Arbejdsrapport fra Miljøstyrelsen, 62/1995 og 70/1995-76/1995) og Miljøvurdering af emballager til øl og læskedrikke (Arbejdsrapport fra Miljøstyrelsen, 21/1996)

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Abstract:
This report is part of a life cycle assessment (LCA) comparing the potential environmental impacts associated with different existing or alternative packaging systems for beer and carbonated soft drinks that are filled and sold in Denmark. The study compares refillable and disposable glass and PET bottles and steel and aluminium cans and is an update of a previous study carried out in 1992-1996. This report is the technical report on energy and transport scenarios.

Terms:
life cycle assessment; packaging systems; beer; soft drinks; transport; distribution; energy consumption

Supplementary notes:
The project comprises the main report (Environmental Project, 399), and 7 supplementary reports:
Refillable Glass Bottles (Environmental Project, 400), Disposable Glass Bottles (Environmental Project, 401),
Aluminium Cans (Environmental Project, 402), Steel Cans (Environmental Project, 403),
Refillable PET Bottles (Miljøprojekt, 404), Disposable PET Bottles (Miljøprojekt, 405),
Energy and Transport Scenarios (Miljøprojekt, 406).
The previous reports were published in Danish: Miljømæssig kortlægning af emballager til øl
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This report is part of a life cycle assessment (LCA) comparing the potential environmental impacts associated with different existing or alternative packaging systems for beer and carbonated soft drinks that are filled and sold in Denmark. The study compares refillable and disposable glass and PET bottles and steel and aluminium cans and is an update of a previous study carried out in 1992-1996. This report is the technical report on energy and transport scenarios.

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