Emission Reduction of Greenhouse Gases from the Cement Industry

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Abstract

5% of global carbon dioxide emissions originates from cement production. About half of it from calcination and half of combustion processes. A wide range of options exists to reduce CO_2 emissions considerably.

Introduction

Cement is considered one of the most important building materials around the world. It is mainly used for the production of concrete. Concrete is a mixture of inert mineral aggregates, e.g. sand, gravel, crushed stones, and cement. Cement consumption and production is closely related to construction activity, and therefore to the general economic activity. Cement is one of the most produced materials around the world. Due to the importance of cement as a construction material, and the geographic abundance of the main raw materials, i.e. limestone, cement is produced in virtually all countries. The widespread production is also due to the relative low price and high density of cement, that limits ground transportation because of the relative high costs. Generally, the international trade (excluding plants located on the borders) is limited, when compared to the global production.

Cement production is a highly energy intensive production process. The energy consumption by the cement industry is estimated at about 2% of the global primary energy consumption, or almost 5% of the total global industrial energy consumption [WEC, 1995]. Due to the dominant use of carbon intensive fuels, e.g. coal, in clinker making, the cement industry is also a major emitter of CO_2 emissions. Besides energy consumption, the clinker making process also emits CO_2 due to the calcining process. The cement industry contributes 5% of total global carbon dioxide emissions. Therefore Ecofys Energy and Environment and Berkeley National Laboratory made for the IEA Greenhouse Gas R&D Programme an assessment to the role of the cement industry in CO_2 production and to carbon dioxide emission reduction options [Hendriks, forthcoming].

In this article we will first discuss the historical development and global distribution of cement production, and we give a short description of the production processes. In the next paragraph an overview is presented of the CO_2 emission related to the production processes, followed by an analyse of CO_2 emission reduction options.

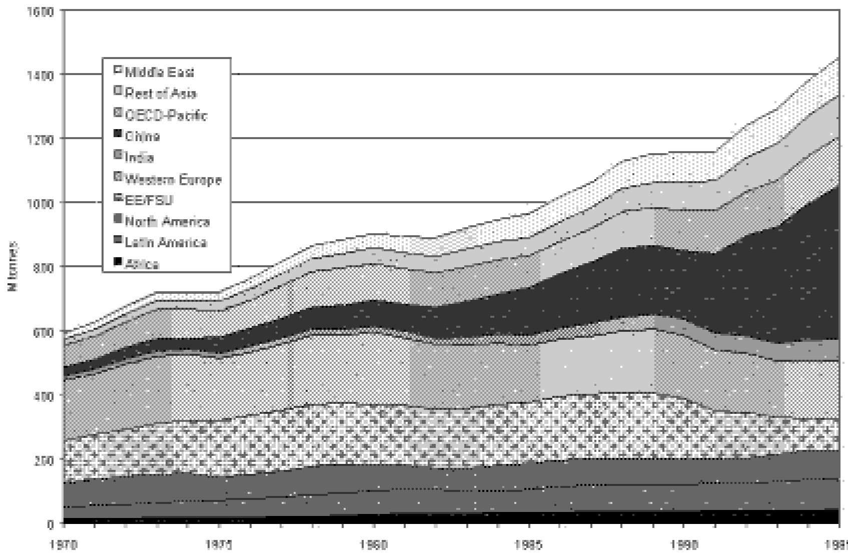
Historical Production Trends in the Cement Industry

Global cement production grew from 594 Tg(1) in 1970 to 1453 Tg in 1995 at an average annual growth rate of 3.6% [Cembureau, 1998]. <Table 1> provides historical cement production trends and average annual growth rates for 10 world regions and countries. The regions with the largest production levels in 1995 were China (including Hong Kong), Europe, OECD-Pacific, Rest of Asia, and the Middle East. The largest average annual growth between 1970 and 1995 was seen in the China (12.2% per year), Rest of Asia (7.8% per year), Middle East (7.4% per year), and India (6.6% per year) regions. Growth in Africa (4.5% per year), Latin America (4.1% per year), and OECD-Pacific (3.3% per year) was also relatively high. In contrast, there was very little growth in production in the North America region, and production levels dropped at an average rate of -0.1% per year in Europe during this period. The Eastern Europe/former Soviet Union region showed the largest declines in cement production, averaging 1.3% per year between 1970 and 1995.

Table 1. Cement Production Trends and Average Annual Growth Rates for Major World Regions, 1970-1995 Source: Cembureau, 1998.

	Cement Production						**Average Annual Growth**	
	1970	**1975**	**1980**	**1985**	**1990**	**1995**	**1970-1995**	**1990-1995**
Region/Country	**Tg**	**Tg**	**Tg**	**Tg**	**Tg**	**Tg**	**%**	**%**
China (incl. Hong Kong)	27	47	81	148	211	477	12.2%	17.7%
Europe	185	194	223	178	196	181	-0.1%	-1.7%
OECD-Pacific	69	83	113	100	126	154	3.3%	4.1%
Rest of Asia	20	31	49	57	89	130	7.8%	8.0%
Middle East	19	29	44	75	93	116	7.4%	4.6%
Latin America	36	52	76	71	82	97	4.1%	3.4%
Eastern Europe/ former Soviet Union	134	177	190	190	190	96	-1.3%	-12.7%
North America	76	73	79	81	81	88	0.5%	1.5%
India	14	16	18	31	49	70	6.6%	7.3%
Africa	15	20	28	35	38	44	4.5%	2.7%
World	594	722	901	965	1156	1453	3.6%	4.7%

Figure 1. Cement Production Trends in Major World Regions, 1970 to 1995. Source: Cembureau, 1998



Source: Cembureau, 1998.

Cement Production Process

Three production steps are distinguished in the description of the production of cement:

- Preparing raw materials: Mixing/homogenising, grinding and preheating (drying) produces the raw meal.
- Burning of raw meal to form cement clinker in the kiln: The components of the raw meal react at high temperatures (900-1500 °C) in the precalciner and in the rotary kiln, to give cement clinker.
- Finish grinding of clinker and mixing with additives: After cooling the clinker is ground together with additives.

The theoretical heat requirement for clinker making, the main substance of cement, is calculated to be about 1.75 ± 0.1 MJ per kg [Taylor, 1992]. The actual heat requirement is higher, and depends on the type of process applied. Cement production processes generally distinguished are wet process, semi-wet process, semi-dry and Lepol process, and dry process. For the production of clinker, two types of kilns are distinguished: rotary kilns and shaft kilns. The former is mainly used in industrialised countries, while the latter is more in use in China [Peikang, 1997]. <Table 2> gives a summary of energy use of the various cement production processes.

Table 2. Summary table of the main energy use (MJ per kg).

	Rotary Kilns				**Shaft Kiln(China)**
	Wet	Lepol	Long dry	Short dry kiln	
Fuel use (MJ/kg)	5.9	3.6	4.2	2.9 - 3.4	3.7 - 6.6
Power use (kWh/kg)	0.025	0.030	0.025	0.022	
Primary energy (MJ/kg)	6.2	3.9	4.5	3.5 - 3.7	

Carbon Dioxide Emissions from the Cement Production Process

Carbon dioxide emissions in cement manufacturing come directly from combustion of fossil fuels and from calcining the limestone in the raw mix. An indirect and significantly smaller source of CO_2 is from consumption of electricity assuming that the electricity is generated from fossil fuels. Roughly half of the emitted CO_2 originates from the fuel and half originates from the conversion of the raw material.

Carbon Dioxide Emission from Calcination (Process Emissions)

Process CO_2 is formed by calcining which can be expressed by the following equation:

$CaCO_3$ -> $CaO + CO_2$
1 kg 0.56 kg+ 0.44 kg

The share of CaO in clinker amounts to 64-67%. The remaining part consists of iron oxides and aluminium oxides. CO_2 emissions from clinker production amounts therefore at about 0.5 kg/kg clinker. The specific process CO_2 emission for cement production depends on the ratio clinker/cement. This ratio varies normally from 0.5 to 0.95.

Carbon Dioxide Emissions from Fuel Use

Practically all fuel is used during pyroprocessing during the production of the clinker. The pyroprocess removes water from the raw meal, calcines the limestone at temperatures between 900 and 1000°C and finally clinker the kiln material at about 1500 °C. The amount of carbon dioxide emitted during this process is influenced by the type of fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels).

The total CO_2 emission during the cement production process depends mainly on:

- Type of production process (efficiency of the process and sub-processes)
- Fuel used (coal, fuel oil, natural gas, petroleum coke, alternative fuels)
- Clinker/cement ratio (percentage of additives)

<Table 3> shows the carbon dioxide emission from the cement production (dry and wet-process) in relation to the clinker/cement ratio and fuel used. The cement/clinker ratio may vary by adding more or less additives to the cement. Not accounted for are the carbon dioxide emissions attributable to mobile equipment used for winning of raw material, used for transport of raw material and cement, and used on the plant site.

Table 3. CO_2 emissions in kg per kg cement produced for dry and wet cement production process for various fuels and various clinker/cement ratios. Assumptions: Electricity use: 0.38 MJe/kg of clinker; Average emission factor of CO_2 of electricity production: 0.22 kg/MJe. Fuel use (dry process): 3.35 MJ/kg of clinker; (wet process): 5.4 MJ/kg of clinker.

	Process emissions	**Process and fuel-related emissions**							
		Dry process				**Wet Process**			
Clinker/ cement	**Clinker**	**Coal**	**Fuel**	**Natural**	**Waste**	**Coal**	**Fuel**	**Natural**	**Waste**

ratio			**Oil**	**gas**			**Oil**	**gas**	
55%	*0.28*	0.55	0.50	0.47	0.36	0.67	0.59	0.53	0.36
75%	*0.38*	0.72	0.66	0.61	0.47	0.88	0.77	0.69	0.47
(Portland) 95%	*0.49*	0.89	0.81	0.75	0.57	1.09	0.95	0.90	0.57

Global Carbon Dioxide Emission from Cement Production Process

In this paragraph we provide an estimate of both process and energy emissions from global cement production in 1994 for ten regions and countries (see <Table 4>). This estimate is based on current, publicly available data for the cement sector. Details on the methodology is given by Hendriks [forthcoming].

World average primary energy intensity was 4.8 MJ/kg cement, with the most energy intensive regions being Eastern Europe and the former Soviet Union (5.5 MJ/kg), North America (5.4 MJ/kg) and the Middle East (5.1 MJ/kg). Estimated carbon dioxide emissions from cement production in 1994 were 1126 Tg CO_2,(2) 587 Tg CO_2 from process emissions and 539 Tg CO_2 from energy use. These emissions account for 5% of 1994 world carbon emissions based on a total of 22.7 103 Tg CO_2 (6.2 GtC) reported by the Carbon Dioxide Information and Analysis Center [Marland, 1998].

The average world carbon intensity of carbon emissions in cement production is 0.81 kg CO_2/kg cement. While China is the largest emitter, the most carbon intensive cement region in terms of carbon emissions per kg of cement produced is India (0.93 kg CO_2/kg), followed by North America (0.89 kg CO_2/kg), and China (0.88 kg CO_2/kg).

Table 4. 1994 Global Carbon Emissions from Cement Production

	Cement Production	Clinker/Cement Ratio	Primary Intensity	Primary Energy	Process Carbon Emissions	Carbon Emissions. Energy Use	Total Carbon Emissions
Region/Country	**Tg**	**%**	**MJ/\kg**	**PJ**	**Tg CO_2**	**Tg CO_2**	**Tg CO_2**
China	423	83%	5.0	2117	175	197	372
Europe	182		4.1	749	73	56	129
OECD Pacific	151		3.5	533	65	41	105
Other ASIA	124		4.9	613	56	179	105
Middle East	111		5.1	563	51	44	95
North America	88		5.4	480	39	40	78
EE/FSU	101		5.5	558	42	38	80
Latin America	97		4.7	462	41	30	71
India	62	89%	5.0	309	28	30	60
Africa	41		4.9	201	18	15	33

World Total	1381		4.8	6585	587	830	1126

Reduction of Carbon Dioxide Emissions

Emissions of carbon dioxide can be reduced by:

- improvement of the energy efficiency of the process
- shifting to a more energy efficient process (e.g. from (semi) wet to (semi) dry process)
- replacing high carbon fuels by low carbon fuels
- applying lower clinker/cement ratio (increasing the ratio additives/cement): blended cements.
- application of alternative cements (mineral polymers)
- removal of CO_2 from the flue gases

These options will be discussed in this section.

Energy Efficiency Improvement and Shifting to More Energy Efficient Processes

Improvement of energy efficiency reduces the emissions of carbon dioxide from fuel and electricity use, and may reduce the costs of producing cement. Improvement may be attained by applying more energy efficient process equipment and by replacing old installations by new ones or shifting to complete new types of cement production processes.

Energy efficiency improvement possibilities:

- conversion from direct to indirect firing
- improved recovery from coolers
- installation of roller presses, vertical mills and high efficiency separators.

By far the largest proportion of energy consumed in cement manufacture consists of fuel that is used to heat the kiln. Therefore the greatest gain in reducing energy input may come from improved fuel efficiency.

Another approach to improve energy efficiency is to shift to another cement production technology. In general it can be said that the dry process is much more energy efficient than the wet process, and the semi-wet somewhat more energy efficient than the semi-dry process. The processes are exchangeable to a large extent, but the applicability also depends on the raw material available. <Table 5> gives the main options to improve the energy efficiency of cement production facilities.

Table 5. Energy efficiency improvement options for cement production processes

Technique	Description	Emission reduction/ energy improvement	Economics
Process Control and Management Systems	Automated computer control may help to optimise the combustion process and conditions	Typically 2.5-5%	Economics of advanced processes very good (pay back time as short as 3 months)
Raw Meal	Use of gravity-type	Reduction power use	No information available

Homogenising Systems	homogenising silos	(1.4-4 kWh/t clinker)	for this study
Conversion from Wet to Semi-Wet Process	Moisture content of raw meal reduced by slurry press filter.	0.8-1.6 GJ/t clinker (3-5 kWh increase of power consumption)	Reduced fuel costs partially off-set the costs.
Conversion from Wet to Semi-Dry Process	Moisture content of raw material reduced through thermal drying system	Estimated at 2 GJ/t clinker. Small increase of power consumption	No capital information available for this study
Conversion from Wet to Dry Process	Complex operation, leaving only the structural parts intact	Estimated at 2.2 GJ/t (increase of power by about 10 kWh/t)	High costs (133 US$/t annual capacity), but vary across the world. May be economically feasible
Conversion from dry to multi-stage preheater kiln	Four or five stage preheating reduces heat losses, and sometimes reduces pressure drop	Depending on original process. In one example reduction from 3.9 to 3.4 GJ/t	Estimated at 30-40 US$/t annual capacity
Conversion from dry to precalciner kiln	Increase of capacity, and lowering specific fuel consumption	Depending on original process. Estimated at 12% (0.44 GJ/t)	Estimated at 28 US$/t annual capacity
Conversion from Cooler to Grate Cooler	Large capacity and efficient heat recovery.	Reduction of 0.1-0.3 GJ/t (increase in power by 3 kWh/t)	Probably only attractive when installing a precalciner simultaneously
Improved Preheating (LEPOL Kiln)	Raw meal preheated in a two-stage grate preheater.	Fuel saving of 6.3% (to 3.3 GJ/t). 1% less power use	Payback time reported to be satisfactory
Optimisation of Heat Recovery in Clinker Cooler	Heat recovery improved by reduction of excess air volume, control of clinker bed depth and new grates.	Estimated at 0.5 GJ/t in the US, and 0.2 GJ/t in India	No specific cost information available for this study
High efficiency Motors and Drives	Variable speed drives, improved control strategies and high-efficiency motors	Estimated power savings ranging from 3 to 8%.	High-efficiency motors cost about the same or only little bit more than regular motors
Adjustable Speed Drives	Reducing throttling and coupling losses by replacing fixed speed AC motors	Estimated at 10 kWh/t cement	Depends strongly on size of system. Estimated at about 1 US$/t cement
Efficient Grinding Technologies	High-pressure mills (like the Horomill) has improved grinding characteristics	Estimated at 16-19 kWh/t (40-50%)	Estimates ranging from 2.5 to 8 US$/t annual capacity. Operation costs may be reduced by 30-40%
High-efficiency Classifiers	Material stays longer in the separator, leading to sharper separation, thus reducing overgrinding	Estimated at 1.7-2.3 kWh/t cement (8%)	Costs are estimated at 2.5-3 US$/t cement
Shaft Kilns:	Improved input control, kiln	Estimated at 1.2 GJ/t	Investment estimated at

Efficient Kiln Technology (China)	size and shape, insulation and computer control.	for the 1990 mix (10-30%)	230 Yuan/t annual capacity. Pay back time of less than 2 years.
Fluidised bed Kiln	Rotary kiln replaced by stationary kiln leading to lower capital costs, wider variety of fuel use and lower energy use	Fuel use of 2.9 to 3.35 GJ/t clinker (also lower NOx emissions)	Lower investment and maintenance costs expected
Advance Comminution Technologies	Non-mechanical 'milling' technologies as ultrasound. Not commercially available in coming decades	Expected (theoretical) savings are large	No information available due to preliminary stage of development
Mineral Polymers	Mineral polymers are made from alumino-silicates leaving calcium oxide as the binding agent.	Preliminary estimates suggests 5 to 10 times lower energy use and emissions	No specific cost information was available for this study.

Replacing High-Carbon Fuels by Low-Carbon Fuels

More than 90% of the energy used in the cement production is originating from fuels. The rest (5-10%) of the primary energy consumption is electricity. A main option to reduce carbon dioxide emissions is to reduce the carbon content of the fuel: e.g. shifting from coal to natural gas. An important opportunity to reduce the (long-cycle) carbon emission is the application of waste-derived alternative fuels. This could at the same time diminish the disposal of waste material and reduces the use of fossil fuels. Disadvantage may be the adverse effects on the cement quality and increased emission of harmful gases. Some types of alternative fuels: Gaseous alternative fuels (Coke oven gases, refinery gases, pyrolisis gas, landfill gas); Liquid alternative fuels (Halogen-free spend solvents, mineral oils, distillation residues, hydraulic oils, insulating oils); and Solid alternative fuels (Waste wood, dried sewage sludge, plastic, agricultural residues, tyres, petroleum coke, tar).

The European cement industry used in 1990 between 0.75 and 1 Tg per year of secondary fuels, equivalent to 25-35 PJ. In 1993, 9% of the thermal energy consumption in the European cement industry originated from alternative fuels [Cembureau, 1997]. A number of issues should be considered while using waste-derived fuels: (i) Energy efficiency of waste combustion in cement kilns; (ii) Constant cement product and fuel quality; (iii) Emissions to atmosphere; (iv) Trace elements and heavy metal; (v) Alternative fate of waste; and (vi) Production of secondary waste.

Waste processing in the cement industries is feasible and current practise. Waste as alternative fuel is increasingly used in cement plants. Waste may reduce CO_2 emissions by 0.1 to 0.5 kg/kg cement produced compared to current used production techniques using fossil fuels. The use of waste generates no additional emissions, although care should be taken for high volatile elements as mercury and thallium. On the other hand, the use of waste does not impair clear environmental advantages, besides the reduction of substituted fossil fuels.

Blended Cements

The production of clinker is the most energy-intensive step in the cement manufacturing process and causes large process emissions of CO_2. In blended cement, a portion of the clinker is replaced with industrial by-products such as coal fly ash (a residue from coal burning) or blast furnace slag (a residue from ironmaking), or other pozzolanic materials (e.g. volcanic material). These products are blended with the ground clinker to produce a homogenous product; blended cement.

The future potential for application of blended cements depends on the current application level, on the availability of blending materials, and on standards and legislative requirements. Worrell [1995] tried to estimate the potential for carbon emission reduction on a national basis for 24 countries in the OECD, Eastern Europe and Latin-America. They estimated the minimum availability of blending materials on the basis of pig iron production and coal combustion. The potential emission reduction varied between 0% and 29%. The average emission reduction for all countries (producing 35% of world cement in 1990) was estimated at 22%. It was negligible for countries with already a large share of blended cement production (e.g. The Netherlands) or with a low availability of blending materials; i.e. countries without iron production or coal fired power stations (e.g. Costa Rica, Guatemala). It is high for countries without much production of blended cements and a well developed industry or fossil based power industry (e.g. United Kingdom, United States) [Worrell, 1995]. The clinker/cement ratio for China is estimated at 85% [Feng, 1995]. Considering the large iron and coal use in power production, a large potential for blended cement may also be expected in the Worlds largest cement maker.

The costs of blending materials depend strongly on the transportation costs, and may vary between 15 and 30 US$/Gg for fly ash and approximately 24 US$/Gg for blast furnace slag. Shipping costs may increase the price significantly, depending on distance and shipping mode. The prices are still considerably lower than the production costs of cement, estimated at approximately 36 US$/Gg (1990) in the United States [Huhta, 1992]

Summarising, the global potential for carbon dioxide emission reduction through producing blended cement is estimated to be at least 5% of total carbon dioxide emissions from cement making (56 Tg CO_2), but may be as high as 20%. The potential savings will vary by country, and even by region.

Carbon Dioxide Removal

Reduction of carbon dioxide emissions can be obtained by applying carbon dioxide removal. In this technique, CO_2 is separated during or after the production process and subsequently stored or disposed of outside the atmosphere. In some cases the recovered CO_2 can be used for other purposes. The CO_2 removal process can be split into three separate steps: recovery of the CO_2 (often including drying and compressing), transport of the CO_2 to a location where it is handled further, and utilisation, storage or disposal of CO_2. The CO_2 can be recovered from the flue gases, originating from the calcination process as well as from the combustion processes. Typical CO_2- -concentrations in the flue gases range from 14 to 33%.

Because of the high share of CO_2 in flue gases originating from the calcination process (and not from a combustion process), combustion in a CO_2/O_2 atmosphere may, a priori, be a promising technique to recover the CO_2. A chemical absorption process seems to be less appropriate because of the high heat requirement of the process.

In the CO_2/O_2 technique oxygen instead of air is used for the combustion, i.e. the nitrogen diluent is removed in an air separation plant before the fuel is oxidised. A problem in this approach is the high stoichiometric combustion temperatures. This problem can be solved, and even turned into an advantage, by recycling produced CO_2. In this way adding more or less recycled CO_2 can control the combustion temperature. The CO_2 in these systems acts as the required temperature moderator. An additional benefit is that all impurities are stored underground, and that the need for DeSOx or DeNOx facilities is not present. Experiences with this technique have been gained in Japan and the United States. In these experiments the main focus lay on the electricity production facilities.

In the scope of this stude a preliminary calculation on the energy requirement has been made: assuming 90% capture efficiency, dry process (3.35 MJ/kg clinker), clinker/ecment ratio of 0.95, and fuel oil as fuel, the total required power consumption will be about 0.86 MJe. The total CO_2 production amounts then to 1.08 kg/kg cement, and the overall capture efficiency amounts to 70%. The nett CO_2 emissions amounts then to 0.32 kg per kg cement (see for comparison <Table 3>).

At this stage of research, however, it is not clear whether this technique can be applied to cement production facilities. Various questions remain unsolved like the influence on the combustion medium on the calcination process, whether or not the process can be sufficiently leak-free. Cost estimates are therefore not available yet.

Conclusions

In 1994 cement industry consumed 6.6 EJ of primary energy, corresponding with 2% of world energy consumption. Worldwide 1126 Tg CO_2 or 5% of the CO_2 production originates from cement production. The carbon intensity of cement making amounts to 0.81 kg CO_2/kg cement. In India, North America, and China the carbon intensity is about 10% higher than on average. Specific carbon emissions range from 0.36 kg to 1.09 kg CO_2/kg cement mainly depending on type of process, clinker/cement ratio and fuel used. On average a little above 50% of the emissions originates from the calcination step.

To reduce the carbon intensity the following options are identified: improving energy effiency, shifting to more energy efficient process, shifting to lower carbon fuels, shifting to lower clinker/cement ratio, shifting to mineral polymers and removal of CO_2.

Seventeen different energy efficiency improvement options are identified. The improvement ranges from a small percentage to more than 25% per option, depending on the reference case (i.e type of process, fuel used) and local situation. The use of waste instead of fossil fuel may reduce CO_2 emissions by 0.1 to 0.5 kg/kg cement (varying from 20 to 40%). On average blended cements may reduce carbon emissions from 0.81 kg to 0.64 kg per kg cement (20%). Global potential of blended cements reducing carbon emissions is at least 5% but it is estimated to be as high as 20%. An end-of-pipe technology to reduce carbon emissions may be CO_2 removal. Probably the main technique is combustion under oxygen while recycling CO_2. However, considerably research is required to all unknown aspects of this technique.

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(1) 1 Tg = 1 million tonne = 10^9 kg

(2) 1 Tg CO_2 = 0.27 Tg C = 0.27 Million tonne Carbon (MtC)

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