CARBON DIOXIDE EMISSION REDUCTION BY INCREASED UTILIZATION OF WASTE-DERIVED FUELS IN THE CEMENT INDUSTRY

Lars-André Tokheim
Telemark University College, Faculty of Technology, Porsgrunn, Norway

Per Brevik
Norcem AS, Brevik, Norway

SUMMARY

Considerable reductions in Norway's emissions of greenhouse gases like CO_2 are required to meet the commitments of the Kyoto Protocol. CO_2 emissions from cement clinker production originate from decarbonation of limestone as well as fuel combustion, and the cement plants in Norway have to comply with requirements given by the pollution control authorities via the national emissions trading system.

There are several ways of reducing CO_2 emissions from the cement industry. Utilizing CO_2-neutral waste fuels as a replacement for fossil fuels is an attractive means of reducing the net CO_2 emissions. Using modern kiln technology is another important measure facilitating lower emissions.

The Norcem plant in Brevik carried out an extensive modernization project in 2004-5, and as a result of this the plant in Brevik currently uses close to 100,000 tons of CO_2-neutral waste-fuels every year. The outcome of this is a reduction in fuel-generated CO_2 emissions of about 25 % from 1995 to 2005.

Reduction of CO_2 emissions by secondary methods such as post-combustion measures using amine absorption for the capture of CO_2 in the exhaust gas from the cement plant is technically feasible, but expensive and risky.

1 INTRODUCTION

There is international consensus that increased emissions of greenhouse gases like carbon dioxide (CO_2) have a negative impact on the global climate through an increased greenhouse effect [1]. The so-called Kyoto Protocol [2], signed by 84 parties on 11 December 1997, recognises this effect, and quantifies CO_2 reduction goals for a number of parties, as a first step in a process to reduce the global emissions of greenhouse gases. The protocol entered into force on 16 February 2005, and per September 2006 the protocol has been ratified by 166 countries, corresponding to 61.6 % of the parties' greenhouse gas emissions in 1990 [3].

Norway's CO_2 emissions are growing; from 1990 to 2004 there was an increase from 34.8 to 44.0 Mt/y, ie 26 %. The total greenhouse gas (GHG) emissions increased from 49.8 to 54.9 Mt/y from 1990 to 2004 [4]; hence the CO_2 part of the GHG emissions is growing. For Norway, the goal of the Kyoto Protocol is to reduce the GHG emissions to a level 1 % higher than the emissions in the reference year 1990 [2]. To reach this goal, a substantial reduction in GHG's is required, and the main focus should be on carbon dioxide.

As an implementation of the Kyoto Protocol, an emissions trading scheme was implemented in Norway on 1 January 2005 [5; 6], covering the CO_2 emissions from 52 industrial plants, including the two Norwegian cement plants in Brevik and Kjøpsvik, owned and operated by Norcem AS, part of HeidelbergCement Group.

This paper discusses the CO_2 reduction potential in the cement industry, describes actions that have been taken to reduce the emissions at Norcem Brevik, summarizes the results of these actions, and discusses the remaining reduction potential at the Brevik plant.

2 SOURCES AND NATURE OF CO_2 EMISSIONS FROM A CEMENT PLANT

The CO_2 emissions from a cement plant originate partly from the decarbonation of the raw materials ($CaCO_3 \rightarrow CaO + CO_2$), partly from the combustion of carbon (simplified reaction equation: $C + O_2 \rightarrow CO_2$) in the fuels used for providing energy for the overall endothermic reactions taking place in the kiln system.

The energy released during combustion of the fuels mainly comes from the oxidation of carbon and hydrogen. As only carbon combustion gives CO_2 emissions, fuels with a relatively high content of hydrogen (such as natural gas), have lower energy-specific CO_2 emissions than fuels with a relatively low content of hydrogen (such as coal or indeed petcoke).

The part of the CO_2 emissions coming from the raw materials is typically given by the local raw material characteristics and is in general not possible to change very much.

Sometimes the raw materials also contain some organic carbon (typically ranging from 1.5 to 6 g of carbon per kg of clinker [7]) in addition to the carbonate. This organic carbon is (partly or fully) oxidized in the kiln system and will contribute to the total energy input (hence slightly reducing the fuel requirement) and also to the CO_2 emissions.

The fuel-generated CO_2 can be classified as fossil-based or based on renewable energy, depending on what type of fuel that is used. Traditionally, coal is the major fuel used in the cement industry. However, switching to biomass fuels offers a potential reduction in the net CO_2 emissions. Such fuels are considered CO_2-neutral, since the CO_2 emitted from the combustion of these fuels (in a long-term view) will re-cycle between the atmosphere and the biomass.

The Norcem plant in Brevik uses a modern dry-process system with a separate precalciner system for decarbonation of the raw materials. In this system, the gross CO_2 from the raw materials and the fuels typically contribute with 63 and 37 %, respectively.

3 CO_2 EMISSION REDUCTION POTENTIAL IN A CEMENT PLANT

The emissions of CO_2 can be reduced by primary or secondary methods. The former means reducing the net generation of CO_2 in the process, while the latter means applying a CO_2 cleaning method to capture CO_2 in the exhaust gas (more on that in Section 7).

Figure 1 describes different alternatives for reduced CO_2 emissions from the clinker production process. (Reducing cement-specific CO_2 emissions [t_{CO2}/t_{cement}] by reducing the clinker percentage in cement is not considered here.)

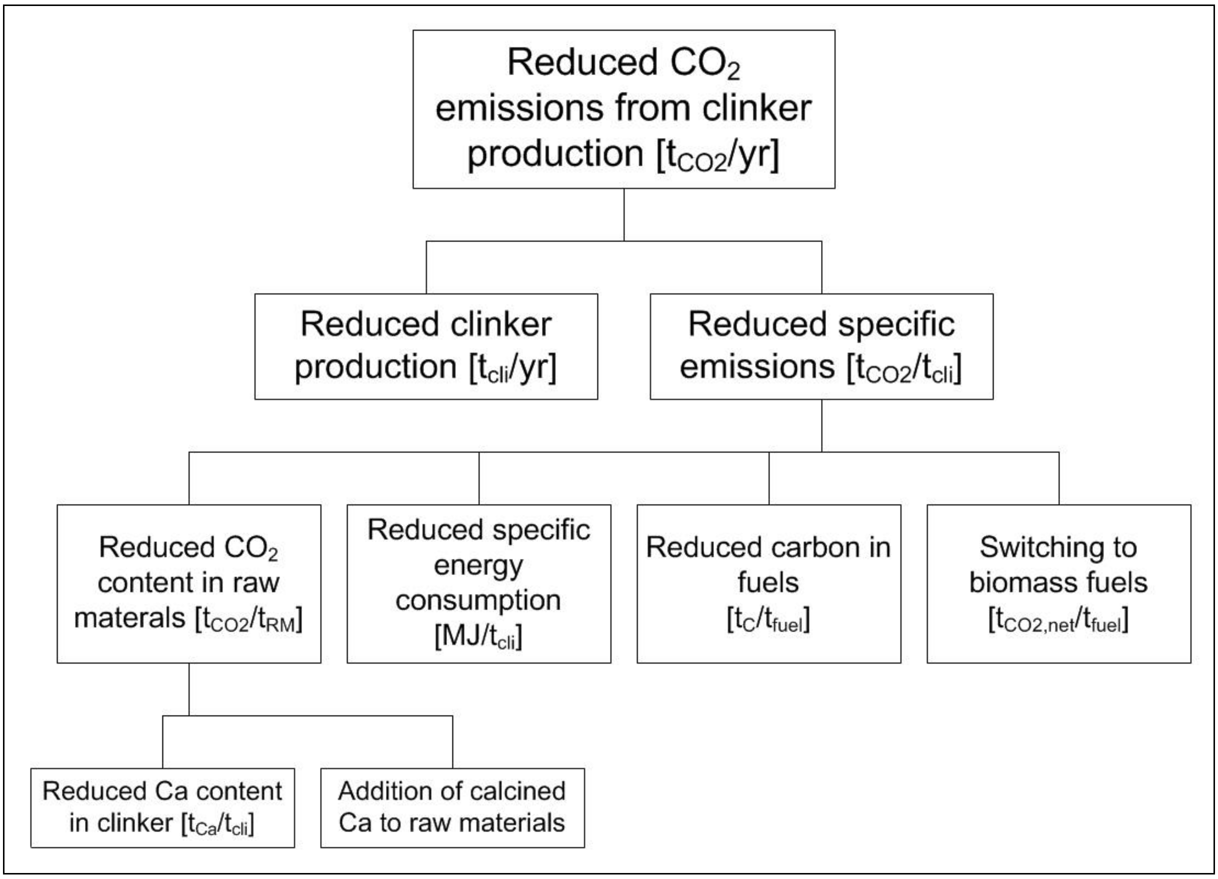

Figure 1: *Options for CO_2 emission reduction from clinker production.*

The obvious possibility of reducing the CO_2 emissions by reducing the actual production of clinker is not further considered here. However, reducing the specific emissions [$t_{CO2}/t_{clinker}$] may give substantial reductions.

As already mentioned, the limestone itself is typically given and can not be easily changed. However, it may be possible to add (a small percentage of) calcined calcium components to the raw mix (for example re-cycled concrete), hence lowering the raw material generated CO_2 emissions. Moreover, it may be possible to switch to other clinker recipes, requiring less calcium and hence giving reduced CO_2 emissions from calcination of limestone. However, these measures may negatively affect the quality of the clinker and is not further considered here.

Focusing on the fuels seems to offer the best opportunities for CO_2 emission reductions.

The gross CO_2 emissions coming from the fuels mainly depend on two factors; the production technology and the energy-specific carbon content of the fuels [kg_{CO2}/MJ] (as discussed above).

The energy efficiency generally increases with more modern technology. Hence, processes applying energy efficient technology consume a lower amount of fuel per ton of clinker produced, meaning that the fuel-generated CO_2 fraction is lower in such systems. Table 1 gives some typical figures for specific energy consumption in different types of kiln systems.

Table 1: *Specific thermal energy consumption of different process types applied for clinker production [7].*

Process type	**Specific energy consumption [MJ/$t_{clinker}$]**
Wet process long kilns	5000-6000
Dry process long kilns	up to 5000
Semi-dry/semi-wet processes (Lepol kilns)	3300-4500
Dry process kilns equipped with cyclone preheaters	3100-4200
Precalciner kilns and dry process rotary kilns equipped with multi-stage cyclone preheaters	ca 3000

Using average values from Table 1, assuming a typical CO_2 content (35 %) in the raw materials and some typical fuel characteristics (lower heating value 27 MJ/kg; energy-specific CO_2 emission 96 kg/GJ), the fuel-generated CO_2 emissions from different production processes can be calculated. The result is given in Figure 2, which clearly demonstrates the CO_2 reduction potential of applying modern technology.

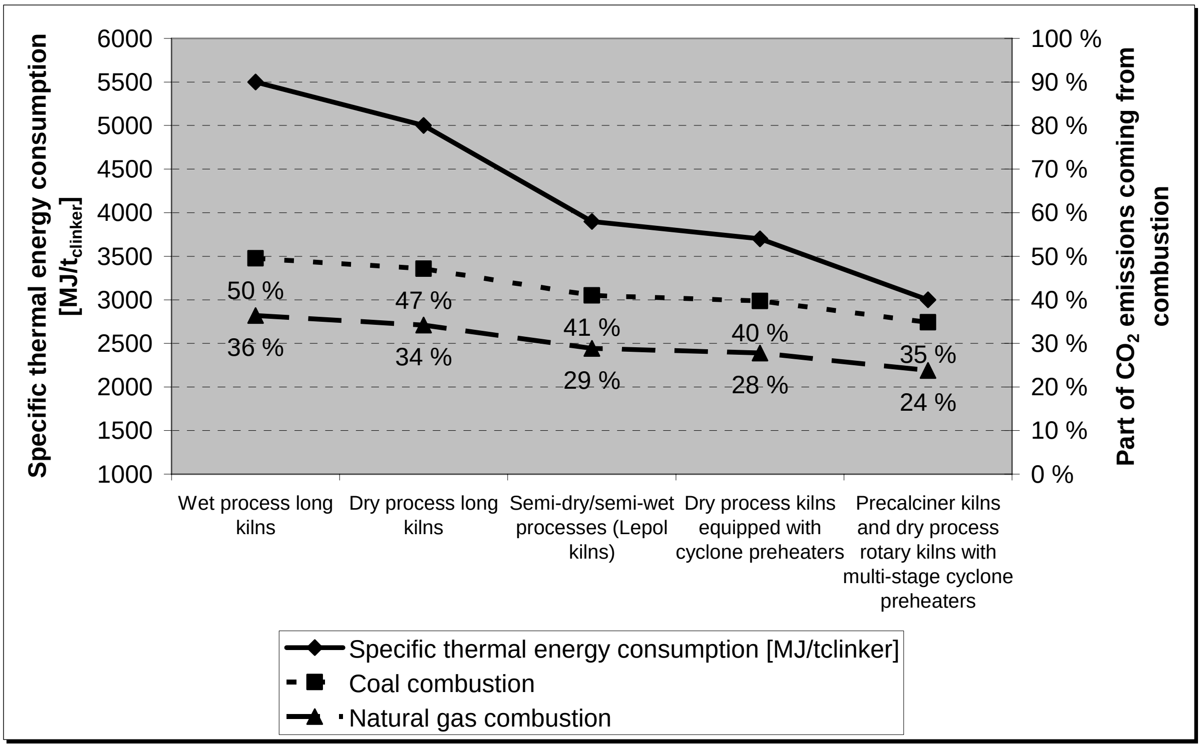

Figure 2: *Different clinker production process types with different specific energy consumption (as given in Table 1), giving rise to different emissions of fuel-generated CO_2; the calculated values are based on 35 % CO_2 in raw materials and either coal (27 MJ/kg; 96 kg_{CO2}/GJ) or natural gas (46 MJ/kg; 56 kg_{CO2}/GJ) as the only fuel.*

Switching from high-carbon to low-carbon fuels is another way of reducing CO_2 emissions. Typically, coal has an energy-specific CO_2 emission of 96 kg/GJ [8], whereas the corresponding value for natural gas, which contains a considerable part of the chemical energy as hydrogen, is around 56 kg/GJ [8]. Hence, by switching from pure coal-firing to pure gas-firing, the fuel-generated part of the CO_2 emissions will drop by some 10-15 percentage points, provided the specific thermal energy consumption stays the same. (The fuel-generated CO_2 emissions will drop by more than 40 %.) This effect is also shown in Figure 2.

Some alternative (biomass) fuels have lower energy-specific CO_2 emissions than coal, others have higher emissions (more about this in Section 5). Hence, carbon content is not the main reason for switching from coal to biomass. Even if the gross (absolute) emissions of CO_2 stay the same – or even increase slightly – the net CO_2 emissions are reduced when replacing coal (or other fossil fuels) by biomass fuels since the latter behave as CO_2-neutral fuels. This means that, when choosing among different types of waste fuels, it is of vital importance to pick the waste fuels that contain a considerable fraction of biomass.

4 THE NORWEGIAN EMISSIONS TRADING SYSTEM AND REPORTING OF CO_2 EMISSIONS

From 1 January 2005, an emissions trading (ET) system was launched in Norway. The Norwegian cement industry (Norcem), as well as 50 other industrial plants in Norway, was asked to apply for allowances for emissions of CO_2 for the years 2005-2007.

Based on historical emission data (baseline years of emissions), the different plants applied for allowances. On average, the Norwegian plants were assigned allowances corresponding to about 95 % of the baseline emissions. These allowances were assigned for free.

Plants with emissions higher than those given by their allowances will have to buy allowances in the market. And, vice versa, plants with emissions lower than those corresponding to the allowances may sell their excess allowances to other players in the market. It is the intention of the Norwegian authorities to link the Norwegian ET system to the ET system in the European Union, but this link has not been established at the time of writing.

In the case of Norcem Brevik, the baseline years were 1998-2001, and the assigned allowances were 904.133 t/yr. (Norcem Kjøpsvik, the other Norwegian cement plant, was given allowances corresponding to 399.410 t/yr.)

According to the new regulations [5; 6] the plants have to submit an annual report documenting their CO_2 emissions. The basis of the numbers given in the annual report is subject to audits by the State Pollution Control Authority ("Statens Forurensningstilsyn"; SFT).

In the annual report, the CO_2 emissions are reported based on activity data, ie yearly consumption of raw materials and fuels, a_i [t/yr], and mass-specific emission factors, e_i [t_i/t]. Hence, the total yearly emissions of CO_2, m_{CO2} [t/yr], can be expressed as:

$$m_{CO2} = \sum_i a_i e_i \quad (1)$$

The emission factor e_i of a given fuel stream *i* can be expressed as the product of the lower heating value of the fuel, H_i [GJ/t], and the energy-specific emission factors, e_i' [t_i/GJ]:

$$e_i = H_i e_i' \quad (2)$$

The plants being part of the ET system have to document all activity data and all emission factors for a given year. Moreover, the accuracy of the data have to be documented, and should be below a certain maximum value.

Norcem Brevik made an extensive study documenting the accuracy of the activity data and the emissions factors used at the plant, and it is believed that this documentation of accuracy is sufficient also for future reporting years. For the plant in Brevik, the calculated average accuracy of the activity data was 1.6 %, corresponding to 14.000 t_{CO2}/yr [9; 10]. The calculated average accuracy of the emissions factors corresponded to 1.5 % of the total CO_2 emission, giving an overall CO_2 emission accuracy of about 3.2 % [10; 11].

The importance of trying to reduce either the a_i or the e_i values – or both – is evident from inspection of the formulas (1) and (2).

5 THE CO_2 CHARACTERISTICS OF WASTE-DERIVED FUELS

CO_2-neutral fuels have emission factor values equal to 0 (e_i = 0). Examples of CO_2-neutral fuels used in the cement industry are animal meal and wood chippings. However, it is probably more common to utilize waste fuels which consist of a mixture of material fractions, of which some are CO_2-neutral (biomass, such as wood) whereas others are fossil-based (such as plastic or hazardous waste).

Table 2 gives an overview of waste-fuels used at Norcem Brevik, including emission factors [8], typical heating values and approximate content of fossil material.

Table 2: *Waste fuels commonly used in the cement industry.*

Fuel	H_i [GJ/t]	Gross CO_2 emission factor [kg/GJ]	Gross CO_2 emission factor [t_{CO2}/t]	Fossil fraction	Net CO_2 emission factor, e_i [kg/GJ]	Net CO_2 emission factor, e_i' [t_{CO2}/t]
Coal	29.3	96.0	2.8	100 %	96.0	2.8
Petcoke	33.9	92.8	3.1	100 %	92.8	3.1
Diesel	42.8	74.0	3.2	0 %	0.0	0.0
Waste oil	34.0	74.0	2.5	100 %	74.0	2.5
Plastic	37.7	75.0	2.8	100 %	75.0	2.8
Solid hazardous waste	14.9	74.0	1.1	100 %	74.0	1.1
Liquid hazardous waste	15.7	74.0	1.2	100 %	74.0	1.2
Refuse derived fuels	13.5	87.0	1.2	10 %	8.7	0.1
CCA waste wood	12.6	110.0	1.4	0 %	0.0	0.0
Animal meal	16.8	88.0	1.5	0 %	0.0	0.0
Wood	15.7	110.0	1.7	0 %	0.0	0.0

At Norcem Brevik, the main focus is on increasing the use of refuse derived fuels (RDF), which has a high biomass fraction and is available in considerable amounts on a long-term basis.

It should be mentioned that most waste-derived fuels have heating values below that of fossil fuels like coal, oil and gas. Typically, waste-derived fuels may contain quite a lot of moisture and ash. The moisture increases the gas flow in the system, which means that extra thermal energy has to be added to achieve the correct operational temperatures in the system. Hence, a kiln system applying a high percentage of low-calorific fuels tends to have a high specific thermal energy consumption. This is a drawback of using high waste-fuel percentages. However, in a greenhouse gas perspective, this drawback is more than outweighed by the advantages of reduced CO_2 emissions when using (mainly) CO_2-neutral waste fuels. Hence, although the gross emissions may increase, the net emissions will decrease.

The indirect effect of reduced waste disposal is of course another positive effect of utilizing waste fuels in the cement kiln system. This goes for all types of waste fuels, be it they are CO_2-neutral or not.

6 KILN SYSTEM MODIFICATION AT NORCEM BREVIK FOR REDUCED CO_2 EMISSIONS

At an early stage Norcem recognised the need to reduce the net emissions of CO_2 and hence obtain a more sustainable production process. The main focus has been, and still is, on replacing fossil fuels by CO_2-neutral fuels originating from different types of waste, as this approach represents a sound solution, both environmentally and economically as well as in a social context (handling of wastes that might otherwise have ended up in a waste disposal site).

A key measure to increase the utilization of solid waste-derived fuels was a modification of the kiln system, carried out in several steps from the mid nineties to 2005, but with a major modification carried out in 2004-2005 [12]. The modernized kiln system, featuring a new calciner system and a chlorine bypass system, is shown in Figure 3. In addition to this, the waste feeding system has been upgraded and extended.

Today, Norcem profits from the early actions that have been taken to meet the challenges of the Kyoto Protocol and the CO_2 emissions trading system that is presently operative in Norway.

The net CO_2 emissions from the Norcem plant in Brevik amounted to 880,000 tons in 1990. In 2005, this figure had been reduced to 763,000 tons, ie a reduction of 13 %. This reduction was mainly accomplished by massive efforts to replace coal with (partly) CO_2-neutral fuels. In the same period the clinker-specific emissions were reduced from 834 to 779 kg of CO2 / kg of clinker.

The change in fuel-generated CO_2 emissions during the last 10 years is apparent from Figure 4. A reduction in net specific CO_2 emissions from about 0.30 to about 0.23 $kg_{CO2}/t_{clinker}$ has been accomplished by increasing the use of CO_2-neutral fuels from close to zero in 1995 to around 90,000 t/yr in 2005.

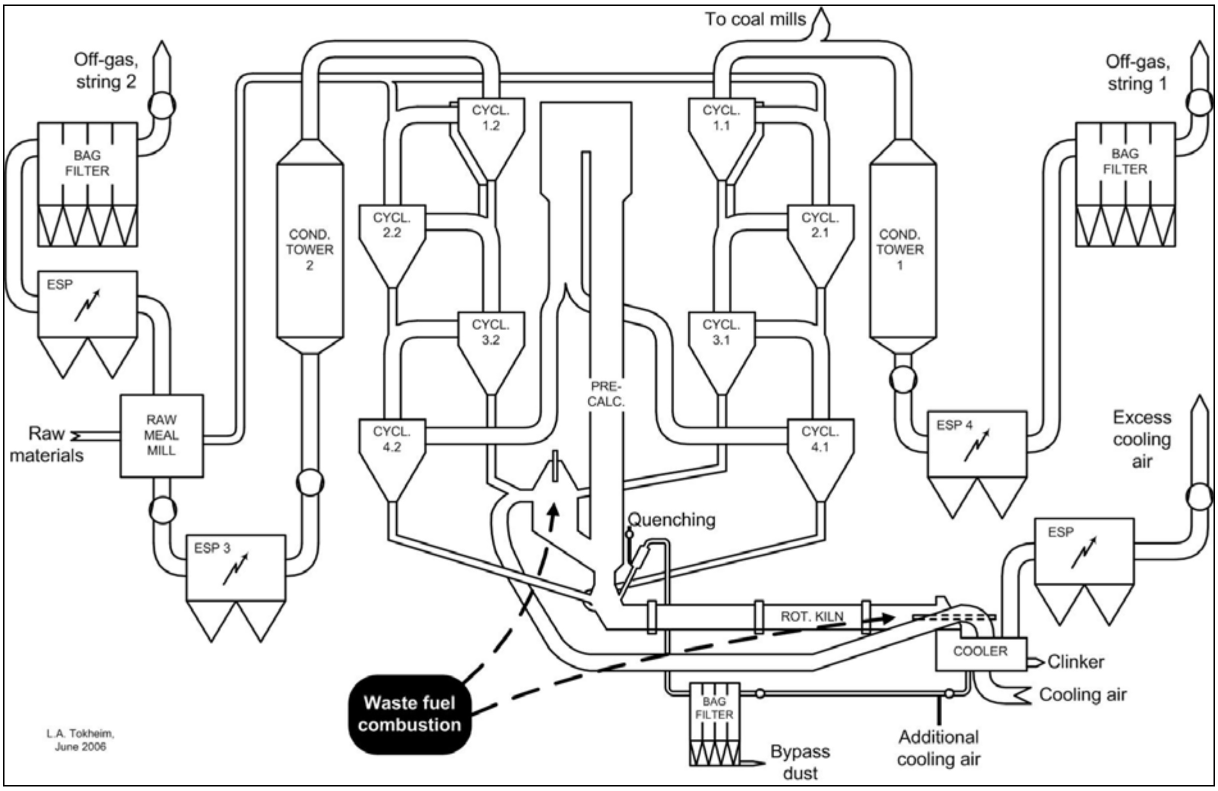

Figure 3: *The modernized kiln system at Norcem Brevik.*

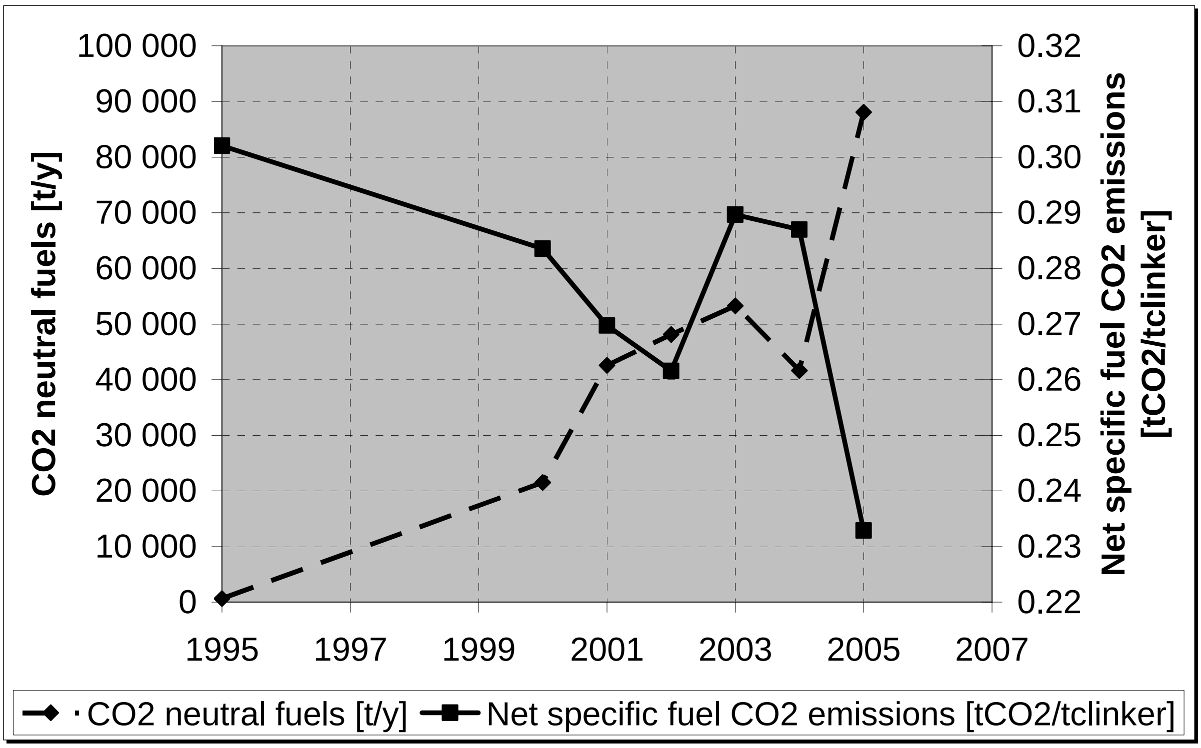

Figure 4: *Reduction in net specific CO_2 emissions by increased use of CO_2-neutral fuels at Norcem Brevik.*

With the modernized kiln system, there is potential for even more reduction in the net CO_2 emissions from the kiln system by increasing the average input of waste fuels in calciner system.

In addition, there is a certain non-utilized potential of reduction in net CO_2 emissions by increasing the percentage of (partly) CO_2-netural fuels in the main burner of the kiln system.

Utilization of raw materials containing calcium in the form of oxides (as an alternative to calcium carbonate) is another measure with a certain potential that Norcem has started to look into, although it is believed that this will be of secondary importance. In this connection it should also be noted that limestone containing considerable amounts of pre-calcined calcium (ie calcium in the form of calcium silicates) tend to be less reactive in the kiln system, hence the use of such limestone qualities – although offering reduced CO_2 emissions – is in general not advocated. Anyway, it is recommended to carry out extensive burnability testing before starting to use such raw materials.

7 CO_2 REDUCTION BY SECONDARY METHODS

Norcem has also investigated the potential of applying exhaust gas cleaning of CO_2 by absorption in an amine solution; see Figure 5. This CO_2 reduction method is usually termed "post-combustion", since the CO_2 is captured after the combustion process is finalized.

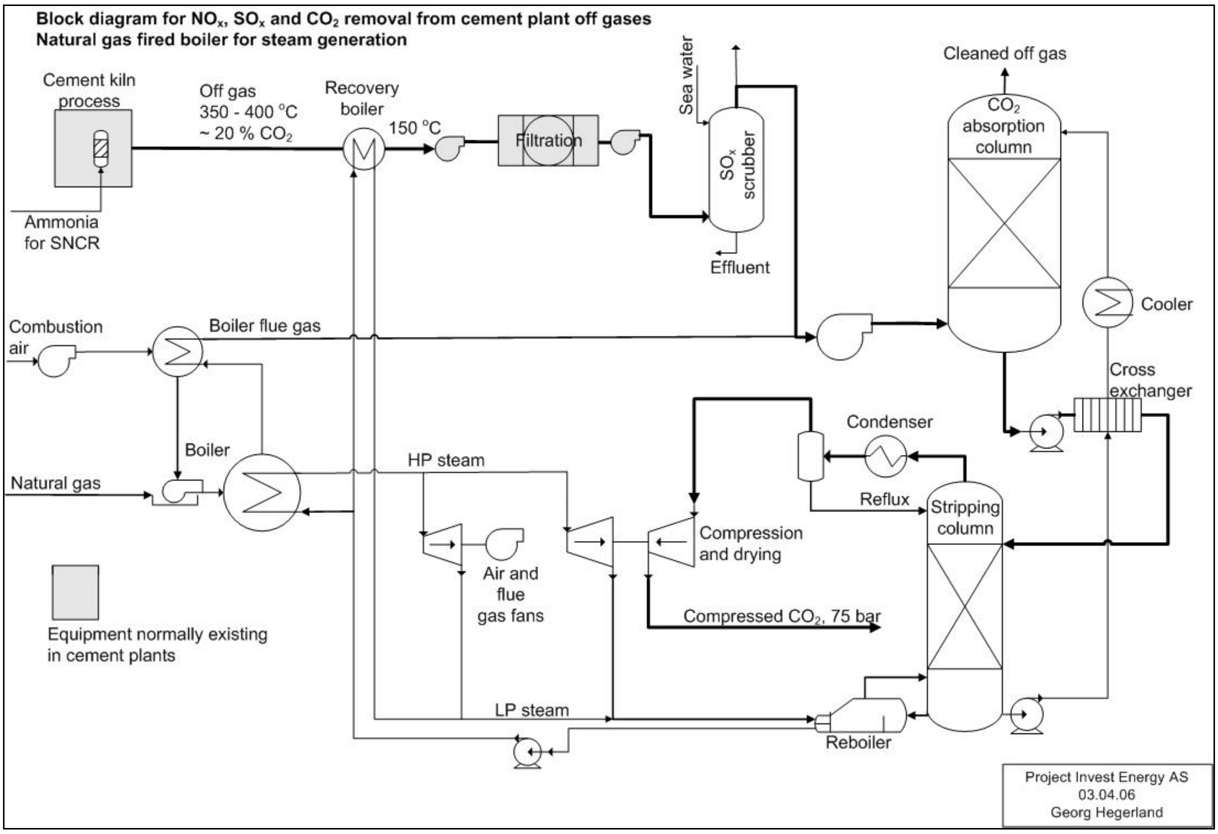

Figure 5: *CO_2 capture from the cement kiln exhaust gas at Norcem Brevik [13].*

Other methods of secondary CO_2 reduction include "pre-combustion" (in which the fuel is reformed before combustion) and "oxy-fuel combustion" (in which pure oxygen is used in the combustion process instead of air), but these methods appear to be less attractive for cement production processes due to high CO_2 emissions originating from the raw materials.

Technically, the post-combustion method can be used to capture the major part (typically about 85 %) of the CO_2 in the off-gas. However, CO_2 capture is very expensive, both when it comes to investments (estimate: MNOK 850 for the Brevik plant) and operational costs (estimate: NOK 260 per ton of captured CO_2) [13].

A full-scale CO_2 capture project would be extremely risky, depending a lot on the oil price as well as the future emissions trading scheme.

8 CONCLUSION

There are several ways of reducing CO_2 emissions from the cement industry. Utilizing (entirely or partly) CO_2-neutral waste fuels as a replacement for fossil fuels like coal is an attractive means of reducing the net CO_2 emissions. Using modern kiln technology is another important measure facilitating lower emissions.

At Norcem Brevik, considerable efforts have been made during the last decade in order to increase the use of waste fuels and hence prepare for the emissions trading system that entered into force in Norway in 2005.

After the last modernization project, carried out in 2004-5, the Norcem plant in Brevik currently uses close to 100,000 tons of CO_2-neutral waste-fuels every year. The result is a reduction in fuel-generated CO_2 emissions of about 25 % from 1995 to 2005.

Reduction of CO_2 emissions by secondary methods such as post-combustion measures using amine absorption for the capture of CO_2 in the exhaust gas from the cement plant is technically feasible, but expensive and risky.

REFERENCES

[1] "Climate Change 2007: The Physical Science Basis. Summary for Policymakers", Intergovernmental Panel on Climate Change, Report, February 2007

[2] "Kyoto protocol to the United Nations Framework Convention on Climate Change", http://unfccc.int/resource/docs/convkp/kpeng.html

[3] http://unfccc.int/files/essential_background/kyoto_protocol/status_of_ratification/application/pdf/kpstats.pdf

[4] "National Inventory Report 2006 – Norway. Greenhouse gas emissions 1990-2004 reported according to the UNFCCC reporting guidelines", Report TA-1281/2006, SFT, 2006

[5] "LOV 2004-12-17 nr 99: Lov om kvoteplikt og handel med kvoter for utslipp av klimagasser (klimakvoteloven)"; http://www.lovdata.no/all/hl-20041217-099.html

[6] "FOR 2004-12-23-1851 Forskrift om kvoteplikt og handel med kvoter for utslipp av klimagasser (klimakvoteforskriften)"; http://www.lovdata.no/for/sf/md/md-20041223-1851.html

[7] "Integrated Pollution Prevention and Control (IPPC): Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries", Report, European Commission, Directorate General, Joint Research Centre, March 2000

[8] ”CO_2 accounting and reporting standard for the cement industry – Version 2.0. The cement CO_2 protocol”, Report, World Business Council for Sustainable Development, June 2002

[9] Tokheim, L.A.: "Bestemmelse av aktivitetsdata ifm. rapportering av CO_2-utslipp" (in Norwegian), Report 9A-R05-009, Norcem Brevik, 2005

[10] "Rapportering for bedrifter med kvotepliktige utslipp av CO_2" (in Norwegian), Annual report to SFT, Norcem Brevik, 2006

[11] Tokheim, L.A.: "Usikkerhet i utslippsfaktorer ifm. rapportering av CO_2-utslipp" (in Norwegian), Report 9A-R06-002, Norcem Brevik, 2006

[12] Tokheim, L.A.: "Kiln system modification for increased utilization of alternative fuels at Norcem Brevik", *Cement International*, No. 4, 2006

[13] Hegerland, G., Pande, J.O., Haugen, H.A., Eldrup, N., Tokheim, L.A. and Hatlevik, L.M.: "Capture of CO2 from a cement plant - technical possibilities and economical estimates", Poster, 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8), Trondheim, Norway, 19-22 June 2006