Final Background Document
on

Cement industry

Prepared in the framework of EGTEI

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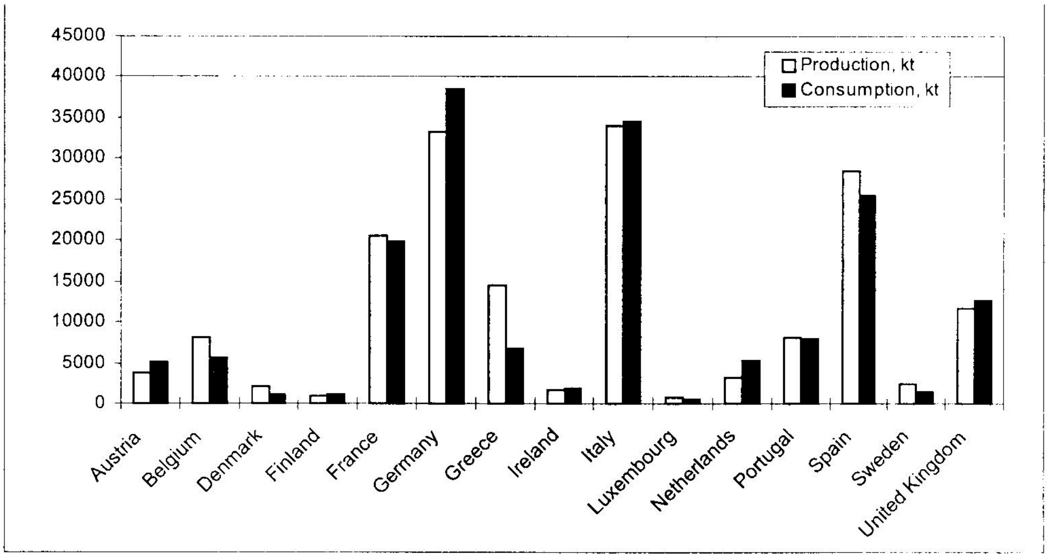
Combustion in the Cement industry

Cement is a hydraulic binder which reacts with water to form calcium silicate hydrates. Different types of cement are known. The term “Portland cement” generally refers to a cement which consists completely or predominantly of cement clinker. Portland slag cement, Portland pozzolona cement etc. consist of a clinker and a ground additive. Additives used in cement production are for example fly ash and residues from iron and steel production. [3]

In 1995 cement production in the European Union totalled 172 million tonnes and consumption 168 million tonnes. 23 million tonnes of cement were imported and 27 million tonnes exported. These figures include trade between EU countries. [1]

Figure 0.1: Cement production in the EU 1995 [1]



The production of cement is carried out in several stages including:

- preparation of the raw materials (crushing, grinding, drying, homogenisation)
- burning of the raw material mixture to produce cement clinker
- preparation of the other cement components
- grinding and mixing of the cement components. [2]

1 General information

1.1 Introduction

SNAP CODE: 03 03 11 - **NFR**: 3c
Sector activity unit: tonne of clinker

Table 1.1: relevant pollutants in the sector

SO_2	**NO_x**	**PM**	**VOC**	**NH_3**
x	x	x	-	-

1.2 Data currently used in the RAINS model

At its present stage of development, the RAINS sector "PR_CEM" represents the production of cement in the PM module. In the SO_2 and the NO_x module, the cement production is aggregated with the lime production in the RAINS sector "IN_PR_CELI". But in future, the RAINS sector "IN_PR_CELI" will be replaced by the more detailed sectors "PR_CEM" and "PR_LIME" (like in the PM module).

1.2.1 Control options for NO_x and SO_2 in the RAINS models

The measures available for reducing emissions from process sources are strongly related to the main production technology. They are site-specific and depend, inter alia, on the quality of raw materials used, the process temperature and on many other factors (fuels used, etc…). Therefore, it is difficult to develop generally valid technological characteristics of control technologies at the same degree of detail as for fuel-related emissions. Thus, for estimating emission control potentials and costs, the emissions from all processes are combined into one group, to which three stages of control can then be applied. Without defining specific emission control technologies, these three stages are represented by typical removal efficiencies with increasing marginal costs of reduction. Data are based on recent information about abatement options for individual industrial processes and their costs as compiled by the UNECE Task Force on Emission Abatement Techniques. However, one should stress that costs of controlling process emissions are burdened with high uncertainties and are subject to change when more detailed information becomes available.[15]

Table 1.2: Control options for NO_x and SO_2 as actually presented in the RAINS model

Pollutant	Abatement technique	Efficiency	Cost per tonne of pollutant avoided in ECUs
SO_2	Option 1	50%	350
	Option 2	70%	407
	Option 3	80%	513
NO_x	Option 1	40%	1,000
	Option 2	60%	3,000
	Option 3	80%	5,000

1.2.2 Control options for PM in the RAINS model

Table 1.3: Unabated emission factors used in the RAINS model for cement production [kg/t cement]

Sector	RAINS Code	$PM_{2.5}$	Coarse[(1)]	PM_{10}	$>PM_{10}$	TSP
Cement production	PR_CEM	23.4	31.2	54.6	75.4	130

(1) coarse particles: > 2.5 and < 10 microns

The RAINS model includes several end-of-pipe control options for the cement industry, particularly fabric filters and electrostatic precipitators.[16]

Table 1.4: Emission abatement techniques applied for PM in the RAINS model

Abatement technique	Unit	Emission factor for PM2.5	Emission factor for PM10	Emission factor for TSP
No control	g/t	23,400	54,600	130,000
Cyclone	g/t	16,380	25,740	33,280
ESP1 (1field)	g/t	1,638	3,199	5,460
ESP2 (2 fields)	g/t	936	1250	1,326
Wet scrubber	g/t	936	1250	1,326
ESP3P (3 fields and more)	g/t	234	267	299
Fabric filter	g/t	234	267	286

Source: **RAINS PM Web** tool (http://www.iiasa.ac.at/~rains/cgi-bin/rains_pm)

1.2.3 Activities for some countries

The baseline of the energy pathway for the EU-15 is defined with the help of the PRIMES model.

Table 1.5: Activities for some countries of the EU-15 (Mt)

Country	**1990**	**1995**	**2000**	**2005**	**2010**
Belgium	6.93	8.22	8.20	7.83	7.83
France	25.74	19.69	19.21	18.98	18.41
Italy	40.49	33.72	38.77	37.97	37.95
Germany New Länder	8.60	8.19	8.65	8.71	9.02
Germany Old Länder	26.34	25.11	26.50	26.71	27.64
Spain	26.58	26.42	35.38	33.66	35.61
United Kingdom	13.57	11.80	12.86	11.31	11.28
…					

Source: **RAINS PM Web** tool (http://www.iiasa.ac.at/~rains/cgi-bin/rains_pm)

2 Definition of reference installation/process

[General remark: The representation of the very heterogeneous glass sector is based on a significantly simplified approach (compromise) - for modeling purposes only. Data proposed for pollutant concentrations or emission factors or any other value are not supposed to be presented as regulatory or limit values.]

The expert group on cement proposes to use **one** reference installation for the whole cement sector and not to take into account the different processes (wet, dry,…).

Considering statistics of the Sevilla BREF document (statistics for the year 1995), the clinker capacity of this single reference installation (C_{ref}) could be defined in the following way:

C_{ref} = (Sector production at EU level / number of kilns) · average clinker content in the cement manufactured = (S_{prod} / N_{kiln}) · $A_{clinkcont}$
$S_{prod} = (172 \cdot 10^6) / 320 = 537{,}500$ tons/day [320 = plant factor, full load operating days/year]
$N_{kiln} = 437$ (in 1995, EU15);

More recent information from CEMbureau gives: number of cement kilns in the 15 EU member states is 397 (Year 2000)
$N_{kiln} = 397$
$A_{clinkcont} = 80\%$

Therefore, the current proposal is:

$C_{ref} = ((172 \cdot 10^6) / 320) / 397 \cdot 0{,}8 = 1{,}083 \approx$ **1,100 tons of clinker per day**

The considered reference installation has an average production capacity of **around 1,100 tons of clinker/day.**

The life time of the kiln is around 35 years (expert estimate) and the plant factor is 320 days per year (expert estimate).

Table 2.1: Reference installation

Reference Code	Technique	Capacity [t/d]	Lifetime [a]	Plant factor [h/a]
01	Average installation	1,100	35	7,680

Remark: An average conversion factor (F_{conv}) between concentrations of pollutants (in mg/Nm^3) and specific mass flows of pollutants (emission factor, in kg per tonne of clinker manufactured) can be calculated using the specific exhaust gas volume per tonne of clinker:

$S_{GasvolSpec}$ = Specific exhaust gas volume generated while manufacturing one tonne of clinker = 2,300 Nm^3/t of clinker [Expert estimate]
$F_{conv} = S_{GasvolSpec} \cdot 10^{-6}$

Concentration of pollutant emitted (in mg/Nm^3) · F_{conv} = Specific mass flow of pollutant emitted (in kg/tonne of clinker manufactured).

3 Dust emission

The best available techniques for reducing dust emissions are the fabric filter and the electrostatic precipitator. BAT emission levels associated with the use of these techniques are between 20 and 30 mg of total suspended matter/Nm^3 on a daily average basis for residual O_2 of 10% and dry gases, which corresponds to the standard expression for the cement sector, (thus, it will not be recalled elsewhere in the document).
According to a plant factor of 320 d/y, the range of the yearly average of the abated emission level is from 16 to 24 mg/Nm^3 [36.8-55.2 g/t of clinker; expert estimate].
At this stage, the expert group on cement has considered one single abatement option called “deduster” (efficient ESP equivalent to bag filter).

Table 3.1: Abatement Measure for dust

Measure Code	Description	Lifetime (a)	Emission factor (mg/Nm³)	Emission factor (g/t of clinker)
00	None	-	56,520	130,000
01	Deduster	10	20	46

Table 3.2: Investments and Operating costs

Measure Code	Description	Efficiency[(1)] (%)	Investment (k€)	Fixed Operating costs* (%/a)	Variable Operating costs (k€/t/a)
00	None	-	0	0	0
01	Deduster (EP or bag filter)	99.96	1,625	4	See table 3.5

* The fixed Operating costs only depend on the capacity – or size - of the installation, i.e. on the investment, and they are expressed as a **percentage of the plant investment** [%/a]
[(1)] theoretical efficiency, because there may be absorbent injection before the filter.

- ✓ **Investments**

ESP

The investment is around **1.5 k€** for the chosen reference installation.

Fabric filter

The investment is around **1.75 k€** for the chosen reference installation.

- ✓ **Variable operating costs**

Variable operating costs are defined as the costs depending on the level of production. Parameters for variable operating costs depend on the type of measure (technology) installed. In this case, we will use the average between variable operating costs of ESP and bag filter. The following table shows the common parameters and prices needed for the calculation of the variable costs.

ESP

Electricity cost $\lambda^e \cdot c^e / 10^3$ [k€/**t**]

- λ^e: additional electricity demand (=new total consumption – old total consumption) [kWh/**t**]
- c^e: electricity price [€/kWh]

The electric power needed for this technique is around 190 kW. [20]
Thus, $\lambda^e = 190 \cdot 24 / 1{,}100$
$= 4.15$ kWh/**t**

$\lambda^e = 4.15$ kWh/**t** $c^e = 0.0569$ €/kWh (value for France)

Labour cost $\lambda^l \cdot c^l$ [k€/**t**]

- λ^l: labour demand [person-year/t]
- c^l: labour cost/wages [k€/person-year]

The number of additional personnel required for the process is taken here as 0.75 person-year.

Thus, the annual personnel costs are:

$AC_{PERS} = 0.75 \cdot c^l$

Thus λ^l = (0.75)/ Capacity

= 0.75/(1,100 • 320)

= $2.13 \cdot 10^{-6}$ person-year/**t**

c^l = 37,234 k€/ person –year (value for France) $\lambda^l = 2.13 \cdot 10^{-6}$ person-year/**t**

Dust disposal cost $\lambda^d \cdot c^d \cdot ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated}$: unabated emission factor of pollutant [t pollutant/**t**]
- λ^d: demand for dust disposal [t/ t pollutant removed]
- c^d: specific dust disposal cost [€/t]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

For the considered technique and efficiency, there is **no waste by-product disposal.**

λ^d = 0 t/ t TSP removed

Fabric filter

Electricity cost $\lambda^e \cdot c^e / 10^3$ [k€/**t**]

- λ^e: additional electricity demand (=new total consumption – old total consumption) [kWh/**t**]
- c^e: electricity price [€/kWh]

The electric power needed for this technique is around 190 kW. [20]
Thus, λ^e = 240 • 24 /1,100
=5.24 kWh/**t**

λ^e = 5.24 kWh/**t** c^e = 0.0569 €/kWh (value €/kWh (value for France)

Labour cost $\lambda^l \cdot c^l$ [k€/**t**]

- λ^l: labour demand [person-year/t]
- c^l: labour cost/wages [k€/person-year]

The number of additional personnel for the process is taken here as 0.75 person-year.

Thus, the annual personnel costs are:

$AC_{PERS} = 0.75 \cdot c^l$

Thus $\lambda^l = (0.75)/ \text{Capacity}$

$= 0.75/(1{,}100 \cdot 320)$

$= 2.13 \cdot 10^{-6}$ person-year/**t**

c^l = 37,234 k€/ person –year (value for France) $\lambda^l = 2.13 \cdot 10^{-6}$ person-year/**t**

<u>Dust disposal cost</u> $\lambda^d \cdot c^d \cdot ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated}$: unabated emission factor of pollutant [t pollutant/**t**]
- λ^d: demand for dust disposal [t/ t pollutant removed]
- c^d: specific dust disposal cost [€/t]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

For the considered technique and efficiency, there is **no waste by-product disposal.**

λ^d = 0 t/ t TSP removed

Table 3.3: Parameters needed to calculate variable Operating costs for primary deduster

	$ef_{unabated}$ [t dust/t]	**η**	**λ^d [t/t dust removed]**	**c^d [€/t]**	**λ^e [kWh/t]**	**c^e [€/kWh]**	**λ^l [person-year/t]**	**c^l [€/person-year]**	**Variable Operating costs (€/t)**
ESP	0.13	99.96	No dust disposal with these techniques		4.15	0.0569	$2.13 \cdot 10^{-6}$	37,234	0.539
Bag filter	0.13	99.96			5.24	0.0569	$2.13 \cdot 10^{-6}$	37,234	0.576

<u>Deduster</u>

To obtain the cost of the secondary measures, the following repartition is taken into account:
50% of ESP
50% of bag filter
According to this repartition, the different costs of the deduster are the following:

Table 3.4: Investments and Operating costs

Measure Code	**Description**	**Efficiency[(1)] (%)**	**Investment (k€)**	**Fixed Operating costs** (%/a)	**Variable Operating costs** (€/t/a)
00	None		0	0	0
01	Deduster (ESP or bag filter)	99.96	1,625	4	0.557

Table 3.5: Parameters for calculating variable operating costs for the deduster

	$ef_{unabated}$ [t dust/t]	η	λ^e [kWh/t]	c^e [€/kWh]	λ^l [person-year/t]	c^l [€/person-year]	λ^d [t/t dust removed]	Variable Operating costs (€/t)
Deduster	0.13	99.96	4.69	0.0569	$2.13 \cdot 10^{-6}$	37,234	0	0.557

The mentioned costs are for the treatment of raw emissions (without any abatement techniques already installed). But in most cases the plant has already implemented a dedusting equipment (ESP or bag filter). Then the specific cost (C_{Dust}) would be derived from the cost mentioned in tables 3.4 and 3.5 to be divided by the marginal mass of pollutant avoided (obtained by the difference between the initial situation (average current concentration or specific mass emission for the whole sector) and the final one (concentration or specific mass emission fixed in the BAT range)).
For example, the plant has already a deduster and achieve a dust abated emission factor EF_{dust} of 100 $g/t_{clinker}$. Then the specific cost C_{dust} for the replacement of the deduster to achieve the BAT range will be :
C_{dust} (in euros per ton of dust avoided) = C (in euros per ton of clinker)/($(EF_{dust} - EF_{BAT})*10^{-6}$)
with :
C: Cost of the deduster defined in the table 3.4
EF_{BAT}: specific mass emission fixed in the BAT range (= 46 g/t clinker).
This measure having a specific cost C_{dust} (in euros per ton of dust avoided) has a maximal implementation rate on the following dust emission expressed in tons :
($(EF_{dust} - EF_{BAT})*10^{-6}$) * yearly activity level (in tons of clinker produced).

The mentioned costs are for the treatment of emissions from the kiln. For other sources such as the mill or the clinker coolers, taking into account that it will be quite impossible to collect information on the specific emissions of these sources and on the application rates of the abatement techniques and that the costs may be not too different than for the kiln, it has been decided by the experts to handle the dust issue for the cement sector considering that all dust emissions are produced by the kiln .

4 NO_x emission

The expert group on cement has proposed the following approach:

An uncontrolled yearly average emission level:
Current proposal concerning concentration: around **1400 mg/Nm³** (experts estimate, considered as being the upper limit of national averages found in member countries)

Use of primary measures with an abatement efficiency of about 25%:
This primary measure comprises some technologies like low NO_x burners, flame cooling, re-circulation, process control, mineralised clinker, etc.
Current proposal for an emission level (as yearly average): **1050 mg/Nm³**

Use of an additional secondary measure (SNCR or SCR) with an average abatement efficiency of 62 %:
This panel of secondary measures may comprises technologies like SNCR or SCR if available. It has nevertheless to be pointed out that SCR has until now only one reference cement plant in Germany which has still to be considered as a full scale test with few feed

back information concerning technical and economical aspects. In addition, SNCR cannot be considered available for the wet process.

Current proposal for an emission level (as yearly average): **400 mg/Nm^3**

Staged combustion has an average efficiency a little bit higher than the panel of primary measures mentioned above. But, few references use this technique and the application rate is very limited. That is why this technique will not be taken into account.

Table 4.1: Abatement Measures for NO_x

Measure Code	**Description**	**Efficiency (%)**	**Emission factor (mg/Nm³)**	**Emission factor (g/t of clinker)**
00	None		1,400	3,220
01	Primary technologies	25	1,050	2,415
02	Primary + Secondary technologies	72	400	920

Table 4.2: Investments and Operating costs

Measure Code	**Description**	**Lifetime (a)**	**Investment (k€)**	**Fixed Operating costs** (%/a)*	**Variable Operating costs** (k€/t)
00	None		0	0	0
01	Primary technologies	8	250	4	$2.64 \cdot 10^{-5}$
02	Secondary technologies	10	600	4	See table 0.14

* The fixed operating costs only depend on the capacity – or size - of the installation, i.e. on the investment, and they are expressed as a **percentage of the plant investment** [%/a]

Variable operating costs are defined as the costs depending on the level of production. Parameters for variable operating costs depend on the type of measure (technology) installed. The following tables show the common parameters and prices needed for the calculation of the variable costs.

4.1.1 Primary technologies

Labour cost $\lambda^l \bullet c^l$ [k€/**t**]

- λ^l: labour demand [person-year/**t**]
- c^l: wages [k€/ person-year]

The number of additional personnel required for the primary measure unit is taken here as 0.25.

Thus, the annual personnel costs are:

$AC_{PERS} = 0.25 \bullet c^l$

Thus λ^l = (0.25)/Capacity

= 0.25/(1,100 • 320)

$= 7.1 \cdot 10^{-7}$ person-year/**t**

$\lambda^l = 7.1 \cdot 10^{-7}$ person-year/**t** c^l = 37,234 k€/ person-year (value for France)

<u>Electricity cost</u> $\lambda^e \cdot c^e / 10^3$ [k€/**t**]

- λ^e: additional electricity demand (= new total consumption – old total consumption) [kWh/**t**]
- c^e: electricity price [€/kWh]

The electric power needed for this technique is around 20 kW. [20]
Thus, $\lambda^e = 20 \cdot 24 /1{,}100$
$=0.44$ kWh/**t**

$\lambda^e = 0.44$ kWh/$t_{clinker}$ c^e = 0.0569 €/kWh (value for France)

4.1.2 Secondary technologies

In this case, to determine the operating cost, the SNCR technology is considered. The different costs are the following:

<u>Electricity cost</u> $\lambda^e \cdot c^e / 10^3$ [k€/**t**]

- λ^e: additional electricity demand (= new total consumption – old total consumption) [kWh/**t**]
- c^e: electricity price [€/kWh]

$\lambda^e = 0.13$ kWh/$t_{clinker}$ c^e = 0.0569 €/kWh (value for France)

<u>Ammonia cost</u> $\lambda^s \cdot c^s \cdot ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated}$: unabated emission factor of pollutant [t pollutant/t]
- λ^s: specific NH_3 demand [t/t pollutant removed]
- c^s: NH_3 price [€/t]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

$\lambda^s = \lambda^m \cdot \lambda^M / \eta$

with:
λ^m: NH_3/NO_x (mol/mol) ratio for NO_x emitted
λ^M: NH_3/NO_x (mol weight/mol weight) ratio

$\lambda^s = 1.5 \cdot (17/46)/0.62$
$= 0.89\ t_{NH3}$/t NO_x removed

$ef_{unabated} = 2.41 \cdot 10^{-3}\ t_{NOx}$/t $\lambda^s = 0.89\ t_{NH3}$/t NO_x removed

c^s = 400 €/t_{NH3} (value for France based on a cost a aqueous ammonia (25% by weight) of 100 euros per tonne)
η = 62 %

Labour cost $\lambda^l \cdot c^l$ [k€/**t**]

- λ^l: labour demand [person-year/**t**]
- c^l: wages [k€/ person-year]

The number of additional personnel required for the SNCR unit is taken here as 0.25 [11]

Thus, the annual personnel costs for the SNCR process are:

$AC_{PERS} = 0.25 \cdot c^l$

Thus λ^l = (0.25)/ Capacity

= 0.25/(1,100 • 320)

= $7.1 \cdot 10^{-7}$ person-year/**t**

$\lambda^l = 7.1 \cdot 10^{-7}$ person-year/**t**
c^l = 37,234 k€/ person –year (value for France)

Table 4.3: Parameters needed to calculate variable Operating costs for secondary technologies

	$ef_{unabated}$ [t NO_x/t]	**η**	**λ^s [t/t NO_x removed]**	**c^s [€/t]**	**λ^e [kWh/t]**	**c^e [€/kWh]**	**λ^l [person-year/t]**	**c^l [€/person-year]**	**Variable Operating costs (€/t)**
Secondary technologies	$2.41 \cdot 10^{-3}$	62	0.89	400	0.13	0.0569	$7.1 \cdot 10^{-7}$	37,234	**0.569**

5 SO_2 emission

The SO_2 emissions are mainly depending on the concentration of sulphur in the raw material and in the fuel burned and also on the technology used to produce cement.

The expert group on cement has proposed a methodology to handle this pollutant:

It is to consider three plant categories according to their initial level of unabated SO_2 emission factor and - in fact - to the abatement technique which should be considered to reach the BAT range:

- Level A: < **400** mg/Nm³: no abatement measure needs to be implemented
- Level B: 400-1,200 mg/Nm³: absorbent injection could be implemented and lead to an emission level below 400 mg/Nm³. For the cost evaluation, the expert group has considered an initial level of **1,000** mg/Nm³.
- Level C: > 1,200 mg/Nm³: wet scrubber could be applied and lead to an emission level below 400 mg/Nm³. For the cost evaluation, the expert group has considered an initial level of **1,600** mg/Nm³.

Table 5.1: Abatement Measures for SO_2

Measure Code	Level of initial emission	Unabated emission factor (mg/Nm³) Taken into account in the economical assessment	Abatement technique	Abated emission factor (mg/Nm³)
00	A	< 400		< 400
01	B	1,000	Absorbent injection	< 400
02	C	1,600	Wet scrubber	< 400

Table 5.2: Investments and variable Operating costs

Measure Code	Description	Removal efficiency (%)	Lifetime (a)	Investment (k€)	Fixed Operating costs (%/a)*	Variable Operating costs (k€/t/a)
00	None	-	-	0	0	0
01	Absorbent injection	60	10	200	4	See table 5.3
02	Wet scrubber	75	10	5,500	4	See table 5.4

* The fixed operating costs only depend on the capacity – or size - of the installation, i.e. on the investment, and they are expressed as a **percentage of the plant investment** [%/a]

Variable operating costs are defined as the costs depending on the level of production. Parameters for variable operating costs depend on the type of measure (technology) installed. The following tables show the common parameters and prices needed for the calculation of the variable costs.

5.1.1 Absorbent injection

The different costs are the following:

Lime cost: $\lambda^s \cdot c^s \cdot ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated}$: unabated emission factor of pollutant [t pollutant/**t**]
- λ^s: specific lime demand [t/t pollutant removed]
- c^s: lime price [€/t]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

with: $\lambda^s = \lambda^m \cdot \lambda^M / \eta$
λ^m: Ca/S (mol/mol) ratio for SO_2 emitted
λ^M: $Ca(OH)_2/SO_2$ (mol weight/mol weight) ratio

$\lambda^s = 2.2 \cdot (74/64) / 60 \cdot 100$
$= 4.24\ t/t_{SO2\ removed}$

$ef_{unabated} = 2.3 \cdot 10^{-3}\ t_{SO2}$ /**t**
η = 60 %
$\lambda^s = 4.24\ t/t_{SO2\ removed}$ (with Ca/S (mol/mol) ratio = 2.2)
c^s = 100 €/t (value for France)

Waste disposal cost $\lambda^d \bullet c^d \bullet ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated:}$ unabated emission factor of pollutant [t pollutant/**t**]
- λ^d: demand for waste disposal [t/ t pollutant removed]
- c^d: specific waste disposal cost [€/t]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

For the considered technique and efficiency, there is **no waste by-product disposal.**

λ^d = 0 t/ t TSP removed

Labour cost $\lambda^l \bullet c^l$ [k€/**t**]

- λ^l: labour demand [person-year/t]
- c^l: labour cost/wages [k€/person-year]

The number of additional personnel required for the process is taken here as 0.25 person-year.

Thus, the annual personnel costs are:

$AC_{PERS} = 0.25 \bullet c^l$

Thus λ^l = (0.25)/ Capacity

= 0.25/(1,100 •320)

= 7.10 •10^{-7} person-year/**t**

c^l = 37,234 k€/ person –year (value for France) λ^l = 7.10 •10^{-7} person-year/**t**

Electricity cost $\lambda^e . c^e / 10^{-3}$ [k€/**t**]

- λ^e: additional electricity demand (= new total consumption – old total consumption) [kWh/**t**]
- c^e: electricity price [€/kWh]

The electric power needed for this technique is around 70 kW.
Thus, λ^e = 70 · 24 /1100
=1.53 kWh/**t**

λ^e = 1.53 kWh/**t** c^e = 0.0569 €/kWh (value for France)

Table 5.3: Parameters needed to calculate variable Operating costs for absorbent injection

	$ef_{unabated}$ [kg SO_2/t]	η	λ^s [t/t SO_2 removed]	c^s [€/t]	λ^d [t/t SO_2 removed]	λ^l [person-year/t]	c^l k€/person-year]	λ^e [kWh/t]	c^e [€/kWh]	Variable Operating costs (€/t)
Absorbent injection	2.3	60	4.24	100	0	7.1•10^{-7}	37,234	1.53	0.0569	**0.698**

5.1.2 Wet scrubber

The different costs are the following:

Limestone cost: $\lambda^s \cdot c^s \cdot ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated}$: unabated emission factor of pollutant [t pollutant/**t**]
- λ^s: specific limestone demand [ton/t pollutant removed]
- c^s: limestone price [€/t]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

with: $\lambda^s = \lambda^m \cdot \lambda^M$
λ^m: Ca/S (mol/mol) ratio
λ^M: $CaCO_3/SO_2$ (mol weight/mol weight) ratio

$\lambda^s = 1.02 \cdot (100/64)$
$= 1.59$ t/$t_{SO2\ removed}$

$ef_{unabated} = 1.74 \cdot 10^{-3}$ t $_{SO2}$ /**t** η = 75 % λ^s = 1.59 t/$t_{SO2\ removed}$ (with Ca/S (mol/mol) ratio = 1.02) c^s = 20 €/t (value for France)

Waste disposal cost $\lambda^d \cdot c^d \cdot ef_{unabated} \cdot \eta / 10^3$ [k€/**t**]

- $ef_{unabated}$: unabated emission factor of pollutant [t pollutant/**t**]
- λ^d: demand for waste disposal [ton/ t pollutant removed]
- c^d: byproduct/waste disposal cost [€/ton]
- η: removal efficiency (= 1 - $ef_{abated}/ef_{unabated}$)

For the considered technique and efficiency, there is **no waste by-product disposal.**

λ^d = 0 t/ t TSP removed

Labour cost $\lambda^l \cdot c^l$ [k€/**t**]

- λ^l: labour demand [person-year/t]
- c^l: labour cost/wages [k€/person-year]

The number of additional personnel for the wet scrubber is taken here as 0.5 person-year.

Thus, the annual personnel costs are:

$AC_{PERS} = 0.5 \cdot c^l$

Thus λ^l = (0.5)/ Capacity

$= 0.5/(1{,}100 \cdot 320)$

$= 1.42 \cdot 10^{-6}$ person-year/t

c^l = 37,234 k€/ person-year (value for France) λ^l = 1.42 •10^{-6} person-year/**t**

Electricity cost $\lambda^e \cdot c^e / 10^{-3}$ [k€/t]

- λ^e: additional electricity demand (= new total consumption – old total consumption) [kWh/t]
- c^e: electricity price [€/kWh]

The electric power needed for this technique is around 375 kW.
Thus, $\lambda^e = 375 \cdot 24 / 1{,}100$
$= 8.18$ kWh/t

λ^e = 8.18 kWh/t c^e = 0.0569 €/kWh (value for France)

Table 5.4: Parameters needed to calculate variable Operating costs for Wet scrubber

	$ef_{unabated}$ [t SO_2/t]	**η**	**λ^s [t/t SO_2 removed]**	**c^s [€/t]**	**λ^d [t/t SO_2 removed]**	**λ^l [person-year/t]**	**c^l [k€/person-year]**	**λ^e [kWh/t]**	**c^e [€/kWh]**	**Variable Operating costs (€/t)**
Wet scrubber	3.68	75	1.59	20	0	1.42•10^{-6}	37,234	8.18	0.0569	**0.606**

6 Parameters for the description of abatement techniques and costs

6.1 NO_x abatement techniques

Table 6.1: Abatement Measure and emission factors for NO_x

Measure Code	Description	Lifetime (a)	Efficiency (%)	EF (kg/t)	EF CI %	Q
00	None		-	3.22		3
01	Primary technologies	8	25	2.41		3
02	Primary + Secondary technologies	10	72	0.92		3

Table 6.2: Investments and Operating costs

Description	Investment (k€)	EF CI %	Q	Fixed Operating costs (%/a)	EF CI %	Q	Variable Operating costs (€/t)	EF CI %	Q	Total Operating costs (€/t)	EF CI %	Q
None	0	-	-	0	-	-	0	-	-	0	-	-
Primary technologies	250		3	4		3	0.0264		3	0.16		3
Primary + Secondary technologies	850		3	4		3	0.595		3	1.27		3

Table 6.3: Parameters needed to calculate variable Operating costs

Description	λ^e [kWh/t]	λ^s [t/t NO_x removed]	λ^l [person-year/t]	λ^{cat} [m³/t]	lt^{cat} [10^3 hrs]
None		-	-	-	-
Primary technologies	0.44	-	$7.1 \cdot 10^{-7}$-	-	-
Primary + Secondary technologies	0.57	0.89	$1.42 \cdot 10^{-6}$	-	-

6.2 Dust abatement techniques

Table 6.4: Abatement measure and emission factors for dust

Primary Measure Code	Description	Lifetime (a)	EF PM_{TSP} (g/t)	EF CI %	Q	EF PM_{10} (g/t)	EF CI %	Q	EF $PM_{2.5}$ (g/t of clinker)	EF CI %	Q
00	None	-	130,000		3	n.i.		3	n.i.		3
01	Deduster	10	46		3	n.i.		3	n.i.		3

n.i.: no information

Table 6.5: Investments and Operating costs

Description	Investment (k€)	EF CI %	Q	Fixed Operating costs (%/a)	EF CI %	Q	Variable Operating costs (€/t/a)	EF CI %	Q	Total Operating costs (€/t)	EF CI %	Q
None	0	-		0	-		0	-		0	-	
Deduster	1,625	-	3	4		3	0.557		3	1.31		3

Table 6.6: Parameters needed to calculate variable Operating costs

	λ^d [t/t dust removed]	λ^e [kWh/t]	λ^l [person-year/t]
None	-	-	-
Deduster	0	4.69	$2.13 \cdot 10^{-6}$

No fugitive emissions of the process are considered.

6.3 SO_2 abatement techniques

Table 6.7: Abatement measure for SO_2

Measure Code	Abatement technique	Lifetime (a)	Removal efficiency (%)	Unabated emission factor (kg/t)	Abated emission factor (kg/t)	EF CI %	Q
00	-	-	-	0.92	-	-	3
01	Injection absorbent	10	60	2.3	0.92	-	3
02	Wet scrubber	10	75	3.68	0.92	-	3

Table 6.8: Investments and variable Operating costs

Description	Investment (k€)	EF CI %	Q	Fixed Operating costs (%/a)	EF CI %	Q	Variable Operating costs (€/t)	EF CI %	Q	Total Operating costs (€/t)	EF CI %	Q
None	0	-	3	0	-	3	0	-	3	0	-	3
Injection absorbent	200	-	3	4	-	3	0.698	-	3	0.791	-	3
Wet scrubber	5,500	-	3	4	-	3	0.606	-	3	3.16	-	3

Table 6.9: Parameters needed to calculate variable Operating costs

	λ^{lime} [t/t SO_2 removed]	$\lambda^{limestone}$ [t/t SO_2 removed]	λ^d [t/t SO_2 removed]	λ^l [person-year/t]	λ^e [kWh/t]
None	-	-	-	-	-
Injection absorbent	4.24	-	0	$7.1 \cdot 10^{-7}$	1.53
Wet scrubber	-	1.59	0	$1.42 \cdot 10^{-6}$	8.18

7 Data to be provided by national experts for the completion of the database for their own country

The following tasks are required:

7.1 **Validation work**

For representing costs in this sector, the national expert is invited to comment the methodology defined by the EGTEI Secretariat.

- Validation of investments provided and,
- Validation of the method of derivation of operating costs.

Or

- Provide other costs for the same combination of techniques and justify them.

Comments have to be sent to the Secretariat within the two weeks after having received the document.

7.2 Provision of specific data

Tables to be filled in by national experts:

7.2.1 Country specific data

Determination of country specific data to calculate variable costs (they are valid for all stationary sources and only have to be entered in the ECODATA tool once)

Table 7.1**:** Country-specific data

Parameters	Costs
Electricity price [€/kWh]	
Wages [€/person-year]	
Ammonia price [€/t_{NH3}]	
Lime cost [€/t_{lime}]	
Limestone cost [€/$t_{limestone}$]	

7.2.2 Activity level on Reference installations

Respective share of the total activity level (in t clinker produced/year) for each reference installation in 2000, 2005, 2010, 2015, 2020.

The different reference installations have been defined according to their initial level of unabated SO_2 emission factors and - in fact - to the abatement technique which should be considered.

Table 7.2:Definition of the three reference installations

RIC	Description
01	Level A: < 400 mg/Nm³
02	Level B: 400 –1,200 mg/Nm³

03	Level C: > 1,200 mg/Nm³

Table 7.3**:** Activity levels on Reference Installations (t clinker produced / year)

RIC	2000	2005	2010	2015	2020
01					
02					
03					
Total	Calculated automatically by the tool				

- If no prevision on the structure of this sector is available (for 2005 to 2020), the proportions used in 2000 can be used.

7.2.3 Average clinker content in the cement manufactured

The numbers given in the technical document relate to the production of clinker, not cement. The clinker content in the final cement is supposed to be 80%. Clinker contents differing significantly from this percentage in a given country should be specified.

Table 7.4: Average clinker content in the cement manufactured

	Default data mean	User input mean
$\mathbf{A_{clinkcont}}$	80%	

7.2.4 Fuel consumption

Table 7.5**:** Fuel consumption (GJ/year)

	2000	2005	2010	2015	2020
Natural gas					
Heavy fuel oil					
Waste					
Solid fuels					
Biomass					

Table 7.6**:** Fuel characteristics

	S content [wt-%]	Lower heat value [GJ/t]
Natural gas		
Heavy fuel oil		
Solid fuels		
Waste		
Biomass		

7.2.5 Unabated emission factor

Table 7.7: Unabated emission factor [kg/t clinker]

Pollutants	Default data mean	CI %	User input mean	CI %
EF NOx	3.22	-		
EF PM_{TSP}	130	-		
EF PM_{10}	-	-		
EF $PM_{2.5}$	-	-		
Reference installation 1				
EF SO_2	Country specific data	-		
Reference installation 2				
EF SO_2	Country specific data	-		
Reference installation 3				
EF SO_2	Country specific data	-		

7.2.6 Application rate and applicability

Respective percentage of reduction measures in 2000 for each reference installation as well as if possible, the percentage of use in 2005, 2010, 2015, 2020 and applicability according to the definition used in the RAINS model.

NO_x abatement measures

Table 7.8: Application rate and applicability for NO_x abatement measures

Description	**Application rate in 2000 [%]**	**Application rate in 2005 [%]**	**Applicability [%]**	**Application rate in 2010 [%]**	**Applicability [%]**	**Application rate in 2015 [%]**	**Applicability [%]**	**Application rate in 2020 [%]**	**Applicability [%]**
None									
Primary technologies			100		100		100		100
Secondary technologies			100		100		100		100

- To support provision of this information, you are invited to use the following methodology:

Methodology to calculate the different application rates:

The different input parameters to determine the application rates are:

- E_{NOx}: Emission of NO_x in a country (t per year) for the different years
- N_a: Activity level (t of clinker per year) for the different years

Then, the sector situation may be defined by:

$$F_{s\,a\,NOx} = (E_{NOx}/N_a)$$

Using this result, it is then possible to calculate the different application rate:

F_{S1NOx}: Uncontrolled NO_x emission level

F_{S2NOx}: NO_x emission level implementing the DeNOx stage 1 technical option (primary measures - PM)

F_{S3NOx}: NO_x emission level implementing the DeNOx stage 2 technical option (secondary measures - SM)

- ✓ If $F_{S1NOx} < F_{s\,a\,NOx} < F_{S2NOx}$, it can be considered that some primary measure may still be implemented to a given percentage of the production capacity.

The virtual application rate of primary measures $T_{1,NOx}$ is obtained by:

$$T_{1,NOx} = (F_{s\,a\,NOx} - F_{S1NOx})/(F_{S2NOx} - F_{S1NOx})$$

- ✓ If $F_{s\,a\,NOx} < F_{S2NOx}$ it may be considered that some secondary measures have already been implemented. In this case, it can be considered that the application rate concerning NO_x primary measures is 100%.

The virtual application rate of secondary measures $T_{2,NOx}$ is obtained by:

$$T_{2,NOx} = (F_{s\,a\,NOx} - F_{S2NOx}) / (F_{S3NOx} - F_{S2NOx})$$

Dust abatement measures

Table 7.9: Application rate and applicability for dust abatement measures

Description	**Application rate in 2000 [%]**	**Application rate in 2005 [%]**	**Applicability [%]**	**Application rate in 2010 [%]**	**Applicability [%]**	**Application rate in 2015 [%]**	**Applicability [%]**	**Application rate in 2020 [%]**	**Applicability [%]**
None									
Deduster			100		100		100		100

- To support provision of this information, you are invited to use the following methodology:

Methodology to calculate the different application rates:

The different input parameters to determine the application rate T_{Dust} are:

- ✓ E_{Dust}: Emission of dust in a country (t per year) for the different years
- ✓ N_a: Activity level (t of clinker per year) for the different years.

Then, the sector situation may be defined by:

$$F_{s\,a\,Dust} = (E_{Dust}/N_a)$$

with: $F_{s\,a\,Dust} = F_{S2Dust} \cdot T_{Dust} + F_{S1Dust} \cdot (1-T_{Dust})$

F_{S1Dust}: Uncontrolled dust emission level

F_{S2Dust}: Emission level after Dedusting

Then:

$$T_{Dust} = ((E_{Dust}/N_a) - F_{S1Dust}) \cdot (1/(F_{S2Dust} - F_{S1Dust}))$$

<u>SO_2 abatement measures</u>

Table 7.10: Application rate and applicability for SO_2 abatement measures

Description	**Application rate in 2000 [%]**	**Application rate in 2005 [%]**	**Applicability [%]**	**Application rate in 2010 [%]**	**Applicability [%]**	**Application rate in 2015 [%]**	**Applicability [%]**	**Application rate in 2020 [%]**	**Applicability [%]**
Reference installation 1									
None									
Reference installation 2									
None									
Injection absorbent			Dust application rate		Dust application rate		Dust application rate		Dust application rate
Reference installation 3									
None									
Wet scrubber			Dust application rate		Dust application rate		Dust application rate		Dust application rate

- For helping to provide the information , use the following methodology.

<u>Methodology to calculate the different application rate:</u>

- *Injection absorbent*

The different input parameter to determine the application rate T_{Inj} are:

- ✓ E_{SOx2}: Emission of SO_2 in a country (t per year) for the different years for the RI 02
- ✓ E_{SOx2un} : Initial (before treatment if any are implemented) or unabated emission of SO_2 in a country (t per year) for the different years for the RI 02
- ✓ N_{aSOx2}: Activity level (t of clinker per year) for the different years for the RI 02

Then, the sector situation may be defined by:

$$F_{s\,a\,SO2} = (E_{SOx2}/N_{aSOx2})$$

with: $F_{s\,a\,SO2} = F_{S1SOx} \cdot T_{Inj} + F_{S2SOxun} \cdot (1- T_{Inj})$

$F_{S2SOxun}$: Initial (before treatment if any are implemented) or uncontrolled SO_2 emission level for a given country concerning RI 02 = E_{SOx2un}/ N_{aSOx2}

F_{S1SOx}: SO_2 emission level after implementing the DeSOx technical option (in this case absorbent injection)

Then:

$$T_{Inj} = ((E_{SOx2}/ N_{aSOx2}) - F_{S2SOx\,un}) \cdot (1/(F_{S1SOx:}- F_{S2SOx\,un}))$$

- *Wet scrubber*

The different input parameter to determine the application rate T_{Wet} are:

- ✓ E_{SOx3}: Emission of SO_2 in a country (t per year) for the different years for the RI 03
- ✓ E_{SOx3un} : Initial (before treatment if any are implemented) or unabated emission of SO_2 in a country (t per year) for the different years for the RI 03

- ✓ N_{aSOx3}: Activity level (t of clinker per year) for the different years for the RI 3

Then, the sector situation may be defined by:

$$F_{s\ a\ SOx3} = (E_{SOx3}/N_{aSOx3})$$

with: $F_{s\ a\ SOx3} = F_{S1SOx} \cdot T_{Wet} + F_{Sox3un} \cdot (1 - T_{Wet})$

F_{SOx3un} Uncontrolled SO_2 emission level for a given country concerning RI 03 = E_{SOx3un}/ N_{aSOx3}

$F_{S1SOx:}$ SO_2 emission level implementing the DeSOx technical option (in this case wet scrubbing)

Then:

$$T_{Wet} = ((E_{SOx3}/ N_{aSOx3}) - F_{Sox3un}) \cdot (1/(F_{S1SOx:} - F_{Sox3un}))$$

Parameters and data listing table
Cement industry

	Parameter	Annotation	Unit	Type of data	Current proposal
1	Activity level SO_2 Reference installation 1	N_{aSOx1}	Tons of clinker per year	Input	
2	Reference installation 2	N_{aSOx2}	Tons of clinker per year	Input	
3	Reference installation 3	N_{aSOx3}	Tons of clinker per year	Input	
4	SO_2 emission Reference installation 1	E_{SOx1}	Tons per year	Input	-
5	Reference installation 2 after treatment	E_{SOx2}	Tons per year	Input	-
6	Reference installation 2 before treatment	$E_{SOx2\ un}$	Tons per year	Input	
7	Reference installation 3 after treatment	E_{SOx3}	Tons per year	Input	-
8	Reference installation 3 before treatment	$E_{SOx3\ un}$	Tons per year	Input	
9	NO_x emission	E_{NOx}	Tons per year	Input	-
10	Dust emission	E_{Dust}	Tons per year	Input	-
11	Natural gas characteristics/consumption			Input	-
12	Heavy fuel oil characteristics/consumption			Input	-
13	Waste characteristics/consumption			Input	-
14	Solid fuels characteristics/consumption			Input	-
15	Biomass characteristics/consumption			Input	-
16	Reference kiln capacity used for the economical assessment	C_{ref}	Tons of clinker per day	Fixed by the experts	1,100
17	Sector production at the EU level	S_{prod}	Tons of clinker per day	BREF information	258,000
18	Number of kilns	N_{kiln}	-	BREF information	397
19	Average clinker content in the cement	$A_{clinkcont}$	%	Fixed by the experts	0.8
20	Conversion factor between concentration in mg/Nm3 and specific mass flow in kg/t of clinker	F_{conv}	-	Fixed by the experts	0.0023
21	Uncontrolled dust emission level	F_{S1Dust}	kg / tonne of clinker	Fixed by the experts	*130*
22	Emission level after Dedusting	F_{S2Dust}	kg / tonne of clinker	Fixed by the experts	*0.046*
23	Cost of the dedusting option per tonne of pollutant avoided (specific for each country or initial situation)	C_{Dust}	Euro	Deduced by a cost evaluation of a dedusting equipment implemented on the reference installation and affecting this cost to the marginal emission avoided.	Country specific data
24	Uncontrolled NO_X emission level	F_{S1NOx}	kg / tonne of clinker	Fixed by the experts	3.22
25	NO_X emission level implementing the DeNOx stage 1 technical option (primary measures - PM) (specific for each country or initial situation)	F_{S2NOx}	kg / tonne of clinker	Fixed by the experts	*2.415*

26	NO_X emission level implementing the DeNOx stage 2 technical option (secondary measures - SM) (specific for each country or initial situation)	F_{S3NOx}	kg / tonne of clinker	Fixed by the experts	*0.92*
27	Cost of the DeNOx stage 1 technical option (PM) per tonne of pollutant avoided	C_{NOX1}	Euro	Evaluated by the experts	227 (case of France)
28	Cost of the DeNOx stage 2 technical option (SM) per tonne of pollutant avoided (specific for each country)	C_{NOX2}	Euro	Evaluated by the experts	740 (case of France)
29	Emission level used to define the first reference installation (emission level below this threshold and not requiring any emission reduction) and to make the different economical assessments (target concerning the emission reduction)	F_{S1SOx}	kg / tonne of clinker	Fixed by the experts	*0.92*
30	Emission level used to define the second reference installation (emission level between F_{S1SOx} and F_{S2Sox} – emission reduction obtained by absorbent injection) and the third reference installation (emission level higher than F_{S2Sox} - emission reduction obtained by wet scrubbing)	F_{S2SOx}	kg / tonne of clinker		*2,76*
31	Uncontrolled emission level taken into account in the economical assessment option 2 (absorbent injection)	F_{S2USOx}	kg / tonne of clinker	Fixed by the experts	*2.3*
	Cost per tonne of pollutant avoided – option 2 absorbent injection (specific for each country)	C_{SOx1}	Euro	Evaluated by the experts	573 (case of France)
32	Uncontrolled emission level taken into account in the economical assessment option 3 (wet scrubbing)	F_{S3USOx}	kg / tonne of clinker	Fixed by the experts	*3.68*
33	Cost per tonne of pollutant avoided – option 3 wet scrubbing(specific for each country)	C_{SOx2}	Euro	Evaluated by the experts	1,144 (case of France)

8 Summarised comparison RAINS/EGTEI

The following table shows the comparison between the abatement techniques in the RAINS model and the techniques proposed by EGTEI.

Table 8.1: Control options for NO_x and SO_2 for the RAINS model and for EGTEI

	RAINS model			EGTEI results		
Pollutant	Abatement technique	Efficiency	Cost per tonne of pollutant avoided in ECUs	Abatement technique	Efficiency	Cost per tonne of pollutant avoided in Euros (for France)
SO_2	Option 1	50%	350	Absorbent injection	60%	573
	Option 2	70%	407	Wet scrubber	75%	1,144
	Option 3	80%	513			
NO_x	Option 1	40%	1,000	Primary technology	25%	227
	Option 2	60%	3,000	Secondary technology	62%	740
	Option 3	80%	5,000			

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