EGTEI

EXPERT GROUP ON TECHNO ECONOMIC ISSUES

ESTIMATION OF COSTS OF REDUCTION TECHNIQUES FOR LCP

Examples of results obtained

EGTEI technical secretariat

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Costs presented here after are based on the methodology developed by EGTEI (Estimation of costs of reduction techniques for LCP – methodology – 30/09/2014) and costs of reduction techniques for LCP EXCEL tool, version a of 30/09/2014.

Emissions to be abated and characteristics of the combustion plant

Examples presented hereafter assume a plant thermal capacity of 1250 MWth (sheet Solid fuels - emission calc.; cell D20) and a capacity factor of the plant (100%, 80% and 50%) using coal (sheet Solid fuels - emission calc.; cell G33). The calculations are presented in details for one case of each pollutant abatement technique (NO_X: LNB, SCR, SNCR; SO_2: LSFO, LSD and DSI FGD with lime; PM: ESP and FF) but are not repeated for other.

The example illustrates the effect of plant capacity and operating hours on NO_X, SO_2 and PM emissions as well as the economic characteristics of the abatement techniques.

These calculations can of course be carried out with other values for thermal capacity and capacity factor.

100% firing of coal from Kleinkopje, is assumed (choice D for detailed, in cell D46, sheet Solid fuels - emission calc.). This coal is a common coal and has a medium amount of ash and sulphur. It has the following composition:

Origin		**Composition of exemplary coals (water and ash free, waf)**					**Ash**	**Moisture**
		C	**H**	**O**	**N**	**S**		
Kleinkopje	South Africa	85.02	4.74	7.33	2.19	0.72	14.49	7.71

With regard to the ash content of the Kleinkopje coal, the coal composition can be given as follows:

Detailed Coal Composition							
	Mass percentages, water and ash free (waf)					Ash	Moisture
	C	H	O	N	S		
Mass-%, abs. [$x_{i,abs}$]	66.15	3.69	5.70	1.70	0.56		

The examples presented hereafter, are building up on the following assumptions concerning the plant operation:

Parameter	**Value**	**Unit**	**EXCEL file sheet**	**Cell**
Reference O_2 content	6	%Vol	Solid fuels - emission calc.	G3
Economic parameters				
Fixed O&M costs	2	% of investment	Solid fuels – emission calc.	G4
Depreciation time	15	years	Solid fuels - emission calc.	J3
Interest rate	4	% per year	Solid fuels - emission calc.	J4
Plant Characteristics				
Gross electric efficiency	40	%	Solid fuels - emission calc.	D21
NO_X	600	mg/Nm^3 dry, ref O_2	Solid fuels - emission calc.	D 24
Boiler and Fuel Characteristics				
Excess air ratio [λ]	1.2		Solid fuels - emission calc.	D40
Carbon in Ash	2	%w/w in ash	Solid fuels - emission calc.	D41
Ash-retained-in-Boiler	5	% of total ash	Solid fuels - emission calc.	D42
S-retained-in-Boiler	0	% of total sulphur	Solid fuels - emission calc.	D43

With a load of 100 % (Solid fuels - emission calc., cell G33), the characteristics of flue gases to be treated are calculated as follows:

According to equation number 2.1-6 the lower heating value (LHV) is calculated with the CHONS composition of the Kleinkopje coal.

$LHV^{fuel} = (33.9 \cdot 66.15 + 117.2 \cdot \left(3.69 - \frac{5.7}{8}\right) + 10.5 \cdot 0.56 - 2.44 \cdot 7.71)/100$ $LHV^{Kleinkopje\ Coal} = 22.44 MJ/kg$	2.1-6

Now the specific dry flue gas volume is calculated according to the equations given by Strauß [Strauß 2006] (D33).

$\dot{v}_{stoich,dry}^{flue\ gas} = \frac{8.899 \cdot (66.15 - 0.3) + 20.96 \cdot 3.69 + 3.32 \cdot 0.56 + 0.80 \cdot 1.7 - 2.64 \cdot 5.7}{100} + \frac{(1.2-1) \cdot 8.899 \cdot (66.15 - 0.3) + 26.514 \cdot 3.69 + 3.342 \cdot 0.56 - 3.340 \cdot 5,7}{100} - \frac{3.69}{2} \cdot 0.22414 = 7.43 \frac{Nm^3}{kg\ fuel}$	2.1-9

Calculation of O_2 correction factor:

As the actual O_2 concentration mostly differs from the reporting O_2 concentration a correction factor needs to be calculated.

$c_{O2,act}[\%] = \frac{(1.2-1) \cdot 6.51}{7.43} \cdot 0.21 \cdot 100 = 3.8$	2.1-28
$f_{O2,corr} = \frac{(21-6)}{(21-3.8)} = 0.87$	2.1-29

With this correlation factor and the specific flue gas volume the specific ash load per Nm^3 of flue gas can be calculated. The same procedure can be done for the specific SO_2 load.

Calculation of ash load:

$load_{ash,dry,O2ref}^{bo} = \frac{0.1449 \cdot (1-0.05)}{7.43 \cdot (1-0.02)} \cdot 0.87 \cdot 10^6 = 16{,}458 \frac{mg}{Nm^3}$	2.1-14

Calculation of SO_2 load:

$load_{SO2,dry,O2ref}^{bo} = \frac{\frac{64.06}{32.06} \cdot 0.56}{7.43} \cdot 0.87 \cdot 10^6 = 1{,}311 \frac{mg}{Nm^3}$	2.1-16

To calculate the total emissions and then the costs for pollutant abatement the annual dry flue gas volume is essential. The annual dry flue gas volume depends on the operating hours (the capacity factor) and the boiler size.

Calculation of annual dry flue gas volume:

$\dot{v}_{annual,dry}^{flue\ gas}[Nm^3] = 7.43 \cdot 3{,}600 \cdot 8{,}760 \cdot CF(50\%\ or\ 80\%\ or\ 100\%) \cdot \frac{bs(1250 MW_{th})}{22.44}$	

Co-Firing Fuel Spec. Used		
Lower Heating Value [LHV^{fuel}]	22.44	MJ/kg LHV
Sulphur mass fraction [x_S]	0.72	% Sulphur w/w
Ash mass fraction [x_{ash}]	14.49	% Ash
Spec. wet flue gas volume [$v^{flue\ gas}_{\lambda,wet}$]	7.9	Nm³ Flue Gas,wet,λ /kg Fuel
Annual wet flue gas volume [$v^{flue\ gas}_{\lambda,wet,year}$]	1.395E+10	Nm³ Flue Gas,wet,λ /year
Spec. dry flue gas volume [$v^{flue\ gas}_{\lambda,dry}$]	7.43	Nm³ flue gas, dry,λ / kg Fuel
Annual dry flue gas volume [$v^{flue\ gas}_{\lambda,dry,year}$]	1.306E+10	Nm³ Flue Gas, dry,λ /year
Oxygen concentration [$c_{O2,act}$]	3.78	% O_2, dry
Oxygen correction factor [$f_{O2,corr}$]	0.87	O_2 corr. Factor to ref. O_2
SO_2 boiler outlet emissions [$load^{bo}_{SO2,dry,refO2}$]	1 311	mg/Nm³ SO_2, dry, ref O_2
NO_x boiler outlet emissions [$load^{bo}_{NOx,dry,refO2}$]	600	mg/Nm³ NO_x, dry, ref O_2
Dust boiler outlet emissions [$load^{bo}_{ash,dry,refO2}$]	16 458	mg/Nm³ dust, dry, ref O_2

It has to be noticed that in this example, no biomass co-firing has been assumed. The characteristics of flue gases to be treated are those corresponding to the use of 100% coal (Solid fuels - emission calc., C96 to E108)

Estimation of NO_X abatement costs (sheet: Solid fuels_NOx Analysis)

For abating NO_X emissions primary and secondary techniques can be implemented. First of all, primary measures such as low NO_X burners (LNB) can be upgraded. As secondary measures Selective Catalytic Reduction (SCR) and Selective Non Catalytic Reduction (SNCR) are considered in these examples. For calculating the economics of these techniques the following assumptions are made:

Catalyst specifications		
Specific Catalyst cost	4000	€/m^3
Specific Catalyst regeneration cost	2500	€/m^3
Catalyst lifetime	20,000	h
Specific catalyst requirement	0.5	M^3/MW_{th}
Stoichiometric ratio	0.9	
Catalyst cost ammonia	450	€/t
Number of catalyst layers	3	
Pressure drop		
Injection & Mixing	1.5	mbar
Catalyst Layer	2.5	mbar
SCR excl Inj., Mix. & Cat.	1.5	mbar
Utility electrical consumption	0.01	MWh/h
Pressure drop constant	0.435	MWh/Mio. Nm^3
Investment data		
Specific investment LNB	6	€/kWth
Specific investment SCR	40	€/kWth

Estimation of LNB costs

NO_X inlet emissions before the abatement techniques are assumed to be 600 mg/Nm³. The objective is to achieve stock emissions of only 200 mg/Nm³ of flue gas. The first question in calculating the economics of primary measures is, if a new LNB should be installed or not. The new oulet emissions of the LNB are mostly given by the manufacturer.

NOx Emissions		
Primary Measures		
Do you want to upgrade 1° measures?	y	Yes/No
New NOx Boiler Outlet Emission	400.0	mg/Nm³ NO_x, dry, ref O_2-%
Reduction achieved with 1°	33.3%	
Gap-Closure to emission goal (% of Cell D108)	50.0%	
Reduction required with 2°	50.0%	

The abated NO_X emissions are calculated

$$load^{bo}_{NOx,dry,O2ref} = 13.06 \cdot 10^9 \cdot (600 - 400) = 2{,}998\ t/a \qquad (2.1\text{-}16)$$

The investment data are derived from survey data and reach from 2.33 to 12.00 €/kW$_{th}$. For simplicity reasons a value of 6 €/kW$_{th}$ is assumed in the example. The specific investment is multiplied with the plant thermal capacity. With the rate for fixed operation and management and interest rate for the investment the fixed operational costs and the capital costs can be calculated. The sum of both ads up to the total costs per year of a LNB.

$$C_{inv,LNB}[€] = 6\left[\frac{€}{kW_{th}}\right] \cdot 1{,}250[MW_{th}] \cdot 1{,}000 = 7.5 \cdot 10^6 € \qquad (3\text{-}1)$$

$$C_{cap,LNB} = 7.5 \cdot 10^6 \cdot \frac{(1+0.04)^{15}}{(1+0.04)^{15} - 1} \cdot 0.04 = 674{,}558\ €/year \qquad (3\text{-}2)$$

$$C_{op,fix,LNB}[€] = 7.5 \cdot 10^6 \cdot 0.02 = 150{,}000\ € \qquad (3\text{-}3)$$

$$C_{tot,LNB}\left[\frac{€}{year}\right] = 674{,}558 + 150{,}000€ = 824{,}558\ €/year \qquad (3\text{-}4)$$

$$c_{NO_X,abated}\left[\frac{€}{t \cdot year}\right] = \frac{824{,}558\ €}{2998t} = 275 \frac{€}{t \cdot year}$$

Primary Measures (LNB)	**100%**	**80%**	**50%**	**Unit**
NOx emissions saved	2,998	2,398	1,499	t/a
Spec. Equipment Investment (see Ref. Box)	6	6	6	€/kWth
Total Investment	7,500,000	7,500,000	7,500,000	€
Capital Cost p.a.	674,558	674,558	674,558	€/a
Fixed O&M Costs	150,000	150,000	150,000	€/a
Total Costs p. a.	**824,558**	**824,558**	**824,558**	**€/a**
spec. NOx reduction costs	**275**	**344**	**550**	**€/t**

Estimation of SCR and SNCR costs

As a next step the secondary measures can be calculated.

The operator of the LCP may choose between a SNCR and a SCR. As said in the working document the variable costs for the SCR are electricity costs for utilities and overcoming pressure drops, reagent costs and costs for catalyst. These costs are calculated as follows:

$PD_{SCR} = 1.5 + 1.5 + 2.5 \cdot 3 = 10.5 mbar$	3-5
$V_{total}^{catalyst} = 0.5 \cdot 1250 = 625 m^3$	3-6
$T_{lifetime,op}^{catalyst} = \frac{20{,}000}{1 \cdot 8{,}760} = 2.28\ years$	3-7
$C_{catalyst} = \frac{625 \cdot 4000 + 2 \cdot 625 \cdot 2500}{2.28} = 2.46 \cdot 10^6 €/year$	3-8

In the secondary measures the NO_X emissions are reduced from 400 mg per Nm^3 to 150 mg. Therefore, the total NO_X abated per year are 3,747 tones. For calculating the necessary reagent a stoichiometric ratio of 0.9 is assumed. Multiplying the necessary reagent amount with the price for ammonia results in about 586 thousand € per year.

$m_{NOx,abated,SCR} = (400 - 150) \cdot 13.06 \cdot 10^9 \left[\frac{Nm^3}{year}\right] \cdot 10^{-9} = 3{,}747 \frac{t}{a}$	3-9
$m_{reagent,SCR} = \frac{17}{44} \cdot 3{,}747 \cdot 0.9 = 1{,}303 \frac{t}{a}$	3-10
$C_{reagent,SCR} = 1{,}303 \cdot 450 = 586{,}308 \frac{€}{year}$	3-11

In the electricity costs the costs are then calculated as given below.

$C_{electricity,SCR} = \left(0.10 \cdot 1 \cdot 8{,}760 + 0.435 \cdot 10.5 \cdot \frac{13.06}{10^6}\right) \cdot 30 = 3.87 \cdot 10^6 \frac{€}{year}$	3-12

The calculation of the primary measures is the same as of the LNB. The total costs of 12.42 million € are then divided by the total NO_X abated by the secondary measures. The specific NO_X abatement costs are 3,314 €.

$C_{inv,SCR} = 40 \cdot 1250 \cdot 1000 = 50 \cdot 10^6 €$	3-13
$C_{cap,SCR} = 312.5 \cdot 10^6 \cdot \frac{(1 + 0.04)^{15}}{(1 + 0.04)^{15} - 1} \cdot 0.04 = 4.5 \cdot 10^6 \frac{€}{year}$	3-14
$C_{op,SCR} \left[\frac{€}{year}\right] = C_{op,fix,SCR} \left[\frac{€}{year}\right] + C_{op,var,SCR} \left[\frac{€}{year}\right]$	3-15
$C_{op,fix,SCR} = 50 \cdot 10^6 \cdot 0.02 = 1.00 \cdot 10^6 \frac{€}{year}$	3-16
$C_{op,var,SCR} = 586{,}308 + 3.87 \cdot 10^6 + 2.463 \cdot 10^6 = 6.92 \cdot 10^6 \frac{€}{year}$	3-17
$C_{tot,SCR} = (4.5 + 6.92 + 1.00) \cdot 10^6 € = 12{,}420 \cdot 10^6 \frac{€}{year}$	3-4

$$c_{NO_X,abated} = \frac{12.420 \cdot 10^6}{3,747} = 3,314 \frac{€}{t \cdot year}$$	

Secondary Measures - SCR (if SCR = Y)	**100%**	**80%**	**50%**	**Unit**
SCR (Y/N)	Y	Y	Y	Y/N
NOx emissions saved	3,748	2,998	1,874	t/a
Capital Costs				
Spec. Equipment Investment	40	40	40	€/kWth
Total Investment	50,000,000	50,000,000	50,000,000	€
Capital Cost p.a.	**4,497,055**	**4,497,055**	**4,497,055**	**€/a**
Operating Costs				
Fixed O&M Costs	1,000,000	1,000,000	1,000,000	€/a
Anhydrous NH_3 (Y/N)	y	Y	Y	
Urea (Y/N)	N	N	N	
Stoichiometric Ratio	0.90	0.90	0.90	
reagent consumption	1,303	1,042	652	t/a
reagent cost	586,401	469,120	293,200	€/a
utility electricity consumption	0.100	0.100	0.100	MWh/h
utility electricity cost	52.560	42.048	26.280	€/a
pressure drop cons.	0.435	0.435	0.435	MWh/Mio. Nm³
pressure drop cost	3,821,058	3,056,846	1,910,529	€/a
annualised catalyst costs	2,463,750	1,971,000	1,231,875	€/a
Operating Costs (incl. Catalyst Costs) p. a.	**7,923,769**	**6,539,015**	**4,461,884**	**€/a**
Total Costs p. a.	**12,420,824**	**11,036,070**	**8,958,939**	**€/a**
spec. NOx reduction cost	**3,314**	**3,681**	**4,781**	**€/t**
share capital costs to total costs	**36.2%**	**40.7%**	**50,2%**	
share operating costs to total costs	**63.8%**	**59.3%**	**49,8%**	

The SNCR has limits to efficiency depending on the plant size and the NO_X concentrations. In the given case that was calculated for SCR with a reduction from 400 mg/Nm³ to 150 mg/Nm³ literature does not suggest SNCR as the efficiency of NO_X reduction is only about 35% in plants larger than 700 MW_{th}.

Secondary Measures		
NOx emissions before 2° measures	400	mg/Nm³ NO_x, dry, ref O_2-%
Does literature suggest SNCR?	N	Yes/No
New NOx outlet emissions	150.0	mg/Nm³ NO_x, dry, ref O_2-%
Total reduction achieved	75.0%	
Degree of Over-Achievement to ELV	25.0%	

As the reduction from 400 to 150 mg/Nm³ is not feasible with an SNCR we assume here that the NO_X stack emissions are not 150 but 300 mg/Nm³.

Secondary Measures		
NOx emissions before 2° measures	400	mg/Nm³ NO_x, dry, ref O_2-%
Does literature suggest SNCR?	Y	Yes/No
New NOx outlet emissions	300.0	mg/Nm³ NO_x, dry, ref O_2-%
Total reduction achieved	50.0%	
Degree of Over-Achievement to ELV	0.0%	

This leads to a total amount of NO_X abated of 1,499 t/a. The calculation of the SNCR is identical to the calculation of the SCR only that no catalyst is used and the pressure drop is less.

$$PD_{SCR} = 1.5 \tag{3-21}$$

For calculating the necessary reagent a stoichiometric ratio of 1.75 is assumed. Multiplying the necessary reagent amount with the price for ammonia results in about 586 thousand € per year.

$$m_{NOx,abated,SNCR} = (400 - 300) \cdot 13.06 \cdot 10^9 \left[\frac{Nm^3}{year}\right] \cdot 10^{-9} = 1{,}499 \frac{t}{a} \tag{3-18}$$

$$m_{reagent,SNCR} = \frac{17}{44} \cdot 1{,}499 \cdot 1{,}75 = 1{,}013 \frac{t}{a} \tag{3-19}$$

$$C_{reagent,SNCR} = 1{,}013 \cdot 450 = 456{,}089 \frac{€}{year} \tag{3-20}$$

In the electricity costs the costs are then calculated as given below.

$$C_{electricity,SNCR} = \left(0.10 \cdot 1 \cdot 8{,}760 + 0.435 \cdot 1.5 \cdot \frac{13.06}{10^6}\right) \cdot 30 = 130{,}540 \frac{€}{year} \tag{3-22}$$

The calculation of the primary measures is the same as of the LNB. The total costs of 2.79 million € are then divided by the total NO_X abated by the secondary measures. The specific NO_X abatement costs are 1,858 €.

$$C_{inv,SNCR} = 16 \cdot 1250 \cdot 1000 = 20 \cdot 10^6 € \tag{3-23}$$

$$C_{cap,SNCR} = 20 \cdot 10^6 \cdot \frac{(1 + 0.04)^{15}}{(1 + 0.04)^{15} - 1} \cdot 0.04 = 1.79 \cdot 10^6 \frac{€}{year} \tag{3-24}$$

$C_{op,SNCR}\left[\frac{€}{year}\right] = C_{op,fix,SNCR}\left[\frac{€}{year}\right] + C_{op,var,SNCR}\left[\frac{€}{year}\right]$	3-25
$C_{op,fix,SNCR} = 20 \cdot 10^6 \cdot 0.02 = 400{,}000 \frac{€}{year}$	3-26
$C_{op,var,SNCR} = 130{,}477 + 456{,}017 = 586{,}495 \frac{€}{year}$	3-27
$C_{tot,SNCR} = 586{,}495 + 400{,}000 + 1.79 \cdot 10^6 € = 2.785 \cdot 10^6 \frac{€}{year}$	3-4
$c_{NO_X,abated} = \frac{2.785 \cdot 10^6}{1{,}499} = 1{,}858 \frac{€}{t \cdot year}$	

Secondary Measures - SNCR (if SNCR = Y)	**100%**	**80%**	**50%**	**Unit**
SNCR	y	y	y	
NOx emissions saved	1,499	1,199	749	t/a
Capital Costs				
Spec. Equipment Investment	16.0	16.0	16.0	€/kWth
Total Investment	20,000,000	20,000,000	20,000,000	€
Capital Cost p.a.	1,798,822	1,798,822	1,798,822	€/a
Operating Costs				
Fixed O&M Costs	400,000	400,000	400,000	€/a
Anhydrous NH3 (Y/N)	Y	y	y	
Urea (Y/N)	N	N	N	
Stoichiometric Ratio	1.75	1.75	1.75	
reagent consumption	1,014	811	507	t/a
reagent cost	456,017	364,871	228,045	€/a
utility electricity consumption	0,100	0,100	0,100	MWh/h
utility electricity cost	52,560	42,048	26,280	€/a
pressure drop cons.	0.062	0.062	0.062	MWh/Mio. Nm³
pressure drop cost	77,981	62,385	38,990	€/a
Operating Costs p. a.	**986,630**	**869,304**	**693,315**	**€/a**
Total Costs p. a.	**2,785,452**	**2,668,126**	**2,492,137**	**€/a**
spec. NOx reduction cost	**1858**	**2225**	**3325**	**€/t**
share capital costs to total costs	**64.6%**	**67.4%**	**72.2%**	
share operating costs to total costs	**35.4%**	**32.6%**	**27.8%**	

Estimation of FGD costs (sheet: Solid fuels_DeSO2)

3 reduction techniques can be tested with or without low sulphur fuels (LSFO, LSD and DSI FGD).

The target is fixed to 200 mg/Nm³, ref O_2, dry in the example (D6).

The efficiency required is consequently 84.47% ((1311.47-200)/1311.47).

Costs are developed with the following assumptions:

Reagent and by-product prices		
Purity of limestone for LSFO FGD	96	%
Price of limestone for LSFO FGD	40	€/t CaCO3
Purity of lime for LSD FGD	96	%
Price of lime for LSD FGD	80	€/t CaO
Purity of lime for DSI FGD	96	%
Price of lime for DSI FGD	80	€/t CaO

By-products from LSFO FGD		
Commercial price in case of valorisation	-0,15	€/t By-product
By-product disposal (or other destination) costs	20,00	€/t By-product
By-products from LSD FGD		
Commercial price in case of valorisation	0,00	€/t By-product
By-product disposal costs	20,00	€/t By-product
By-products from DSI FGD		
From lime		
Commercial price in case of valorisation	0,00	€/t By-product
By-product disposal costs	40,00	€/t By-product

Tool boxes provide some typical ranges of costs and prices but specific costs or prices can be used, especially country specific costs and prices.

The EXCEL tool offers the opportunity to test the use of low sulphur fuels associated with the reduction technique. If a low sulphur fuel is used, its S content is filled in cell D36 after answering to the question "do you want to use a low sulphur fuel?". The characteristics of the low sulphur fuel are assumed to be the same as the fuel replaced, except the sulphur content (flue gas volume, ash content remain the same).

The use of a low sulphur fuel is tested in this example, when DSI FGD is used. For LSFO FGD and LSD FGD, no low sulphur fuel is used.

Primary Measures		
Do you want to use a lower sulphur content coal?	Y	Yes/No
What is the sulphur content of the coal	0.4	% Sulphur w/w waf
Concentration achieved with low sulphur content fuel	729	mg/Nm³, ref O_2, dry
Gap-Closure to emission goal (% of Cell D6)	52.4	%
Reduction required with secondary measure	72.5	%

The user can decide to go further the limit value fixed previously (D6) to take a margin of uncertainty. The limit to be obtained is fixed to 200 mg/Nm^3. If a lignite is used the coal factor is 1.07. If the retrofit is complex, with a lack of place, the retrofit factor can be increased up 1.3.

The following data are used in the example for LSFO FGD and LSD.

Secondary Measures		
Inlet SO2 concentrations	1311	mg/Nm³, ref O_2, dry
Do you want to estimate costs for LSFO FGD	Y	Yes/No
Do you want to estimate costs for LSD FGD	Y	Yes/No
Do you want to estimate costs for DSI FGD	N	Yes/No
New SO2 outlet emissions	200	mg/Nm³, ref O_2, dry
Total reduction required	84.7	%
Degree of Over-Achievement to ELV	0	%
Retrofit factor	1	
Coal factor	1	

Costs of LSFO FGD

The costs of the measure are calculated without the use of low sulphur fuel:

Primary Measures		
Do you want to use a lower sulphur content coal	N	Yes/No
What is the sulphur content of the coal	0	% Sulphur w/w waf
Concentration achieved with low sulphur content fuel	not valid	mg/Nm³, ref O_2, dry
Gap-Closure to emission goal (% of Cell D7)	n/a	%
Reduction required with secondary measure	84.7	%

Secondary Measures - LSFO FGD (if LSFO FGD = Y)		
LSFO FGD (Y/N)	Y	
SO2 emissions saved	16 661	t SO_2/year
Is there valorisation of waste	Y	Y/N
	Capital Costs	
Adsorber unit cost	*30 369 770*	€
Reagent preparation unit cost	*11 627 236*	€
Waste handling unit cost	*6 109 202*	€
Base balance plant cost	*58 201 428*	€
Total base cost for LSFO FGD	**106 307 637**	€
Indirect installation cost	31 892 291	€
Home office cost	6 909 996	€
Total investment cost	**145 109 924**	€
Capital Cost p.a.	**13 041 346**	**€/year**

The quantity of SO_2 abated is derived from equation 5-12:

$m_{SO2\ abated}^{LSFO\ FGD}\ \left[\frac{t\ _{SO2}}{year}\right] = \left(c_{SO2,in}\left[\frac{mg}{Nm^3}\right] - c_{SO2,load\ emit}\left[\frac{mg}{Nm^3}\right]\right) \cdot \frac{1}{f_{O2,corr}} \cdot \dot{v}_{dry,year}^{flue\ gas}\left[\frac{Nm^3}{year}\right] \cdot 10^{-9}\left[\frac{t}{mg}\right]$	5-1
$m_{SO2\ abated}^{LSFO\ FGD}\ \left[\frac{t\ _{SO2}}{year}\right] = \left(1311\left[\frac{mg}{Nm^3}\right] - 200\left[\frac{mg}{Nm^3}\right]\right) \cdot \frac{1}{0.87} \cdot 13{,}058{,}023{,}445\left[\frac{Nm^3}{year}\right] \cdot 10^{-9}\left[\frac{t}{mg}\right]$	5-12

The quantity of SO_2 abated can also be derived from equation 5-2bis providing the SO_2 load par GJ, the fuel consumption expressed in GJ and the efficiency required for FGD (equation 5.12bis):

$load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right] = \frac{\frac{M_{SO2}\left[\frac{kg}{kmol}\right]}{Ms\left[\frac{kg}{kmol}\right]} \cdot x_S[waf\%].\,10\,\left[\frac{kg\,S}{kg\,fuel}\right] \cdot \left[\frac{100 - x_{ash\,[\%]} - x_{moist}[\%]}{10000}\right] \cdot \left[\frac{100 - x_{S\,retainedinbo}[\%]}{100}\right]}{LHV^{fuel}\left[\frac{MJ}{kg\,fuel}\right]} \cdot 1000\left[\frac{MJ}{GJ}\right]$	5-2 bis
$0.499\left[\frac{kg_{SO2}}{GJ}\right] = \frac{\frac{64\left[\frac{kg}{kmol}\right]}{32\left[\frac{kg}{kmol}\right]} \cdot 0.72[waf\%] \cdot 10\,\left[\frac{kg\,S}{kg\,fuel}\right] \cdot \left[\frac{100 - 14.49 - 7.71}{10000}\right] \cdot \left[\frac{100 - 0}{100}\right]}{22.44\,\left[\frac{MJ}{kg\,fuel}\right]} .1000\left[\frac{MJ}{GJ}\right]$	5-2 bis

$m_{SO2\,abated}^{LSFO\,FGD}\,\left[\frac{t\,_{SO2}}{year}\right] = \left(load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right] \cdot\, cons_e^{fuel}\left[\frac{GJ}{h}\right] \cdot cap\,\frac{[\%]}{100}\,.8{,}760\right) \cdot\, 0.001\left[\frac{t}{kg}\right] \cdot \frac{\eta^{LSFO}}{100}$	5-12bis
$16661\,\left[\frac{t\,_{SO2}}{year}\right] = \left(0.499\left[\frac{kg_{SO2}}{GJ}\right] \cdot\, 4500\left[\frac{GJ}{h}\right] \cdot \frac{100[\%]}{100} \cdot 8{,}760\right) \cdot 0.001\,\cdot\,84.7/100$	5-12bis

For operating costs, it is assumed that by-products are sold as gypsum is produced by LSFO (cell 86). Sale prices are assumed very low due to saturation of the market (-0.15 €/t gypsum cell D20).

The capital cost for the different LSFO FGD units are calculated through equations 5-2 to 5-6. One example is given for the absorber:

$C_{abs}^{LSFO}[€\,] =\, 6{,}074{,}025 \cdot\, r \cdot \left(\left(cf.GHR\left[\frac{GJ}{kWh}\right]\right)^{0.6}\right) \cdot \left(load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right]\right)^{0.02} \cdot (bs\,[MWe])^{0.716}$	5-2
$30{,}370{,}000[€\,] =\, 6{,}074{,}025\,\cdot\,1 \cdot \left(\left(1\,\cdot\,0.009\left[\frac{GJ}{kWh}\right]\right)^{0.6}\right) \cdot \left(0.499\left[\frac{kg_{SO2}}{GJ}\right]\right)^{0.02} \cdot (1250\,\cdot\,0.4\,[MWe])^{0.716}$	5-2

The load of SO_2 is calculated by formula 5-2 bis.

$C_{equip}^{LSFO}[M€\,]$ is equal to 106 M€ (cell D92).

Additional investments due to indirect installation (equation 5-7) and home office costs (equation 5-8) are as follows:

$C_{instal}^{ind}[€\,] = \frac{f_{ec}\,[\%]}{100}\,\cdot\,C_{equip}^{LSFO}[€]$	5-7
$31.9[M€\,] = \frac{30\,[\%]}{100}\,\cdot 106.3[M€]$	5-7

C_{ho}^{ind}[€], are as follows:

$$C_{ho}^{ind}[€] = \frac{f_{ho}[\%]}{100} \cdot (C_{equip}^{LSFO}[€] + C_{instal}^{ind}[€])$$	5-8
$$6.9[M€] = \frac{5[\%]}{100} \cdot (106.3[M€] + 31.9[M€])$$	5-8

Total investment is:

$$C_{inv}^{LSFO}[€] = C_{equip}^{LSFO}[€] + C_{inst}^{ind}[€] + C_{ho}^{ind}[€]$$	5-1
$$145.1[M€] = 106.3[M€] + 31.9[M€] + 6.9[M€]$$	5-1

The annualised capital cost is calculated according to equation 1-3 with the parameters *p* (interest rate) of 4 % and *n* (equipment technical or economic lifetime) of 15 years.

$$C_{cap} = C_{inv} \cdot \frac{(1+p)^n}{(1+p)^n - 1} \cdot p$$	1-3
$$13.05\ M€/year = 106.3 \cdot \frac{(1+0.04)^{15}}{(1+0.04)^{15} - 1} \cdot 0.04$$	1-3

Operating costs

Operating costs are as follows:

	Operating Costs	
Fixed O&M Costs	1 857 505	€/year
Variable Operating costs		
Reagent price	*40*	*€/ton CaCO3*
Specific limestone demand	*1,46*	*t CaCO3/t SO2*
Reagent consumption	*24 276*	*t CaCO3/year*
Reagent cost	971 058	€/year
Electricity price	*60,000*	*€/MWh*
Electricity consumption	*61 040*	*MWh/year*
Electricity cost	3 662 381	€/year
By-product price	-0,15	*€/ton By-product*
By-product generated	2,730	*t By-product/t SO2 abated*
By-product amount	45 484	*t By-product/year*
by-product management cost	-6 823	€/year
Annual operating costs	**6 484 122**	**€/year**

The fixed operating costs are calculated with the following ratio of investment:

$OM_{fix}[\%] = 0.1324.bs^{-0.284}\ [MWth] \cdot 100$	5-9

$1.75[\%] = 0.1324\ \cdot\ 1{,}250^{-0.284}\ [MWth] \cdot 100$	5-9

The percentage is applied on the equipment investment: 1.75 /100 x 106.3 or 1.857 M€/year.

Electricity cost is calculated by equation 5-10:

$C_{elec}^{LSFO}[€\ /year] = bs\ [MWth]\ \cdot\ \frac{\eta^{gross}\ [\%]}{100} \cdot \frac{CAP\ [\%]}{100} \cdot 8{,}760\ \left[\frac{h}{year}\right] \cdot \left(-0.049\ \cdot\ \frac{\eta^{gross}\ [\%]}{100} + 3.3536\right) \cdot \frac{1}{100} \cdot\ C_{elec,spe}\left[\frac{€}{MWh}\right]$	5-10

$3{,}662{,}381[€\ /year] = 1250\ [MWth]\ .\ \frac{40\ [\%]}{100} \cdot\ \frac{100\ [\%]}{100} \cdot 8{,}760\ \left[\frac{h}{year}\right] \cdot \left(-0.049\ \cdot\ \frac{40\ [\%]}{100} + 3.3536\right) \cdot \frac{1}{100} \cdot\ 60\ \ \left[\frac{€}{MWh}\right]$	5-10

Limestone consumption is calculated by equation 5-11 to estimate the demand of $CaCO_3$ per ton of SO_2 abated and then equation 5-13.

$\gamma_{CaCO3}^{S}\left[\frac{t\ CaCO3}{t\ SO2\ abated}\right] = \frac{\left(1.8\ \cdot \frac{\eta^{LSFO}[\%]}{100} -\ 0.1267\right)}{\frac{PUR_{CaCO3}\ [\%]}{100}}$	5-11
$1.46\left[\frac{t\ CaCO3}{t\ SO2\ abated}\right] = \frac{\left(1.8\ \cdot\ \frac{84.7[\%]}{100} -\ 0.1267\right)}{\frac{96\ [\%]}{100}}$	5-11

$C_{CaCO3}^{LSFO}\left[\frac{€}{year}\right] = \gamma_{CaCO3}^{S}\left[\frac{t_{\ CaCO3}}{t_{\ SO2}}\right]\ \cdot\ m_{SO2\ abated}^{LSFO\ FGD}\ \left[\frac{t_{\ SO2}}{year}\right] \cdot\ C_{CaCO3,spe}\left[\frac{€}{t_{\ CaCO3}}\right]$	5-13

$971{,}058\left[\frac{€}{year}\right] = 1.46\left[\frac{t_{\ CaCO3}}{t_{\ SO2}}\right] \cdot 16661\left[\frac{t_{\ SO2}}{year}\right] \cdot\ 40\left[\frac{€}{t_{\ CaCO3}}\right]$	5-13

By-product production (cell D111) and costs of elimination are calculated by equation 5-14 and then equation 5-15:

$\gamma_{bp}^{s}\left[\frac{t_{bp}}{t_{SO2\ abated}}\right] = \gamma_{CaCO3}^{s}\left[\frac{t\ CaCO3}{t\ SO2}\right] \cdot \left(\frac{100 - PUR_{CaCO3[\%]}}{100} \cdot 1 + \frac{PUR_{CaCO3[\%]}}{100} \cdot 1.91\right)\left[\frac{t_{bp}}{t_{CaCO3}}\right]$	5-14
$2.73\left[\frac{t_{bp}}{t_{SO2\ abated}}\right] = 1.48\left[\frac{t\ CaCO3}{t\ SO2}\right] \cdot \left(\frac{100 - 96}{100} \cdot 1 + \frac{96}{100} \cdot 1.91\right)\left[\frac{t_{bp}}{t_{CaCO3}}\right]$	5-14

$C_{bp}^{LSFO}\left[\frac{€}{year}\right] = m_{SO2\ abated}^{LSFO\ FGD}\left[\frac{t_{SO_2}}{year}\right] \cdot \gamma_{bp}^{s}\left[\frac{t_{bp}}{t_{SO_2 abated}}\right] \cdot C_{bp,spe}\left[\frac{€}{t_{bp}}\right]$	5-15
$-6{,}823\left[\frac{€}{year}\right] = 16{,}661\left[\frac{t_{SO_2}}{year}\right] \cdot 2.73\left[\frac{t_{bp}}{t_{SO_2 abated}}\right] \cdot -0.15\left[\frac{€}{t_{bp}}\right]$	5-15

The negative figure obtained indicates a benefit.

Total operating costs (fixed operating costs, electricity consumption costs, reagent costs and byproduct elimination) are 6.484 M€/year.

The total annual cost including annual capital cost is 19.5 M€/year (cell D123).

The summary of costs for LSFO FGD is as follows (cells C117 to E128):

Summary for LSFO FGD : Installation 1250 MWth and 100 % load, coal S: 0.72% waf		
SO_2 emissions avoided	16 661	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	85	%
Total investment	145 109 924	€
Total annual costs	19 535 468	€/year
Spec.SO_2 reduction cost	1 173	€/t SO_2 abated
Spec. investment per kWth	116	€/kWth
Electricity penalty	1.39	%
Share capital costs to total costs	66.8%	
Share operating costs to total costs	33.2%	

If the load is 80%, the costs are as follows:

Summary for LSFO FGD : 1250 MW and load 80%, coal S: 0.72% waf		
SO_2 emissions avoided	13 329	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	85	%
Total investment	145 109 924	€
Total annual costs	18 610 145	€/year
Spec.SO_2 reduction cost	1 396	€/t SO_2 abated
Spec. investment per kWth	116	€/kWth
Electricity penalty	1.39	%
Share capital costs to total costs	70.1%	
Share operating costs to total costs	29.9%	

If the load is 50%, the costs are as follows:

Summary for LSFO FGD : 1250 MW and load 50%, coal S: 0.72% waf		
SO_2 emissions avoided	8 331	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	85	%
Total investment	145 109 924	€
Total annual costs	17 222 160	€/year
Spec.SO_2 reduction cost	2 067	€/t SO_2 abated
Spec. investment per kWth	116	€/kWth
Electricity penalty	1.39	%
Share capital costs to total costs	75.8%	
Share operating costs to total costs	24.2%	

Costs of LSD FGD

The costs of the measure are calculated without the use of low sulphur fuel:

Primary Measures		
Do you want to use a lower sulphur content coal	N	Yes/No
What is the sulphur content of the coal	0	% Sulphur w/w waf
Concentration achieved with low sulphur content fuel	not valid	mg/Nm³, ref O_2, dry
Gap-Closure to emission goal (% of Cell D7)	n/a	%
Reduction required with secondary measure	84.7	%

Secondary Measures - LSD FGD (if LSD FGD = Y)		
LSD FGD (Y/N)	Y	Y/N
SO2 emissions saved	16 661	t SO_2/year
Is there valorisation of waste	N	y/n
Capital Costs		
Absorber unit cost	*31 207 200*	€
Reagent preparation and waste handling units cost	*18 379 623*	€
Base balance plant cost	*46 042 509*	€
Total base cost for LSFO FGD	**95 629 332**	€
Indirect installation cost	28 688 800	€
Home office cost	6 215 907	€
Total investment cost	130 534 038	€
Capital Cost p.a.	**11 740 375**	**€/year**

The quantity of SO_2 abated is derived from equation 5-12:

$m_{SO2\ abated}^{LSFO\ FGD}\left[\frac{t_{\ SO2}}{year}\right] = \left(c_{SO2,in}\left[\frac{mg}{Nm^3}\right] - c_{SO2,load\ emit}\left[\frac{mg}{Nm^3}\right]\right)\cdot\frac{1}{f_{O2,corr}}\cdot\dot{v}_{dry,year}^{flue\ gas}\left[\frac{Nm^3}{year}\right]\cdot 10^{-9}\left[\frac{t}{mg}\right]$	5-12
$m_{SO2\ abated}^{LSFO\ FGD}\left[\frac{t_{\ SO2}}{year}\right] = \left(1311\left[\frac{mg}{Nm^3}\right] - 200\left[\frac{mg}{Nm^3}\right]\right)\cdot\frac{1}{0.87}\cdot 13{,}058{,}023{,}445\left[\frac{Nm^3}{year}\right]\cdot 10^{-9}\left[\frac{t}{mg}\right]$	5-12

The quantity of SO_2 abated can also be derived from equation 5-2bis providing the SO_2 load par GJ, the fuel consumption expressed in GJ and the efficiency required for FGD (equation 5.12bis):

$$load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right]=\frac{\frac{M_{SO2}\left[\frac{kg}{kmol}\right]}{Ms\left[\frac{kg}{kmol}\right]}\cdot x_S[waf\%]\cdot 10\left[\frac{kg\ S}{kg\ fuel}\right]\cdot\left[\frac{100-x_{ash\,[\%]}-x_{moist}[\%]}{10000}\right]\cdot\left[\frac{100-x_{S\,retainedinbo}[\%]}{100}\right]}{LHV^{fuel}\left[\frac{MJ}{kg\ fuel}\right]}.1000\left[\frac{MJ}{GJ}\right]$$	5-2 bis
$$0.499\left[\frac{kg_{SO2}}{GJ}\right]=\frac{\frac{64\left[\frac{kg}{kmol}\right]}{32\left[\frac{kg}{kmol}\right]}\cdot 0.72[waf\%]\cdot 10\left[\frac{kg\ S}{kg\ fuel}\right]\cdot\left[\frac{100-14.49-7.71}{10000}\right]\cdot\left[\frac{100-0}{100}\right]}{22.44\left[\frac{MJ}{kg\ fuel}\right]}.1000\left[\frac{MJ}{GJ}\right]$$	5-2 bis

$$m_{SO2\ abated}^{LSFO\ FGD}\left[\frac{t\ _{SO2}}{year}\right]=\left(load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right]\cdot\ cons_e^{fuel}\left[\frac{GJ}{h}\right]\cdot cap\frac{[\%]}{100}\cdot 8{,}760\right)\cdot\ 0.001\left[\frac{t}{kg}\right]\cdot\frac{\eta^{LSFO}}{100}$$	5-12bis
$$16661\ \left[\frac{t\ _{SO2}}{year}\right]=\left(0.499\left[\frac{kg_{SO2}}{GJ}\right]\cdot\ 4500\left[\frac{GJ}{h}\right]\cdot\frac{100[\%]}{100}\cdot 8{,}760\right)\cdot 0.001\ \cdot\ 84.7/100$$	5-12bis

For operating costs, it is assumed that by-products cannot be sold and byproducts are considered as waste to be disposed (cell D149). Disposal costs are assumed to be (20 €/t byproducts cell D24).

The capital cost for the different FGD units are calculated through equations 5-20 to 5-26.

One example is given for the absorber:

$$C_{abs}^{LSD}[€\,]=\ 6{,}198{,}239\ \cdot\ r\cdot\left(\left(cf.GHR\left[\frac{GJ}{kWh}\right]\right)^{0.6}\right)\cdot\left(load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right]\right)^{0.01}\cdot(bs\ [MWe])^{0.716}$$	5-21
$$31{,}207{,}000[€\,]=\ 6{,}198{,}239\ \cdot\ 1\cdot\left(\left(1\ x\ \ 0.009\left[\frac{GJ}{kWh}\right]\right)^{0.6}\right)\cdot\left(0.499\left[\frac{kg_{SO2}}{GJ}\right]\right)^{0.01}\cdot(1250\ x\ 0.4\ [MWe])^{0.716}$$	5-21

The load of SO_2 is calculated as above by formula 5-2 bis.

$C_{equip}^{LSD}[M€\,]$ is equal to 95.6 M€ (cell D158).

Additional investments due to indirect installation (equation 5-25) and home office costs (equation (5-26) are as follows:

$$C_{instal}^{ind}[€\,]=\frac{f_{ec}\ [\%]}{100}\ \cdot\ C_{equip}^{LSD}[€]$$	5-25
$$28.7[M€\,]=30\frac{[\%]}{100}\cdot 95.6[M€]$$	5-25

$C_{ho}^{ind}[€]$, are as follows:

$$C_{ho}^{ind}[€] = \frac{f_{ho}[\%]}{100} \cdot (C_{equip}^{LSFO}[€] + C_{instal}^{ind}[€])$$	5-26
$$6.21[M€] = \frac{5[\%]}{100} \cdot (95.6[M€] + 28.7[M€])$$	5-26

Total investment is:

$$C_{inv}^{LSD}[€] = C_{equip}^{LSD}[€] + C_{inst}^{ind}[€] + C_{ho}^{ind}[€]$$	5-20
$$130.5[M€] = 95.6[M€] + 28.7[M€] + 6.21[M€]$$	5-20

The annualised capital cost is calculated according to equation 5-3 with the parameters *p* (interest rate) of 4% and *n* (equipment technical or economic lifetime) of 15 years.

$$C_{cap} = C_{inv} \cdot \frac{(1+p)^n}{(1+p)^n - 1} \cdot p$$	5-3
$$11.7 \frac{M€}{year} = 96.4 \cdot \frac{(1+0.04)^{15}}{(1+0.04)^{15} - 1} \cdot 0.04$$	5-3

Operating costs

Operating costs are as follows:

	Operating Costs	
Fixed O&M Costs	1 941 696	€/year
Reagent price	*80*	*€ / ton CaO*
Specific limestone demand	*1,20*	*t CaO/t SO_2*
Reagent consumption	*20 063*	*t CaO/year*
Reagent cost	1 605 048	€/year
Electricity price	*60,000*	*€/MWh*
Electricity consumption	*47 974*	*MWh/year*
Electricity cost	2 878 448	€/year
By-product price	20,00	*€ / ton By-product*
By-product generated	2,783	*t By-product/t SO2 abated*
By-product amount	46 373	*t By-product/year*
by-product management cost	927 461	€/year
Annual operating costs	**7 352 654**	**€/year**

The fixed operating costs are calculated with the following ratio of the capacity:

$$2.03[\%] = 0.1688 \cdot bs^{-0.297}\ [MWth] \cdot 100$$	5-27

The percentage is applied on the equipment investment: 2.03 /100 · 95.6 or 1.942 M€/year.

Electricity cost is calculated by equation:

$$C_{elec}^{LSD}[€\ /year] = bs\ [MWth] \cdot \frac{\eta^{gross}\ [\%]}{100} \cdot \frac{CAP\ [\%]}{100} \cdot 8{,}760\ \left[\frac{h}{year}\right] \cdot \left(-0.039\ \cdot \frac{\eta^{gross}\ [\%]}{100} + 2.6553\right) \cdot \frac{1}{100} \cdot C_{elec,spe}\left[\frac{€}{MWh}\right]$$	5-28

$$2{,}878{,}448[€\ /year] = 1250\ [MWth]\ \cdot \frac{40\ [\%]}{100} \cdot \frac{100\ [\%]}{100} \cdot 8{,}760\ \left[\frac{h}{year}\right] \cdot \left(-0.039\ \cdot \frac{40\ [\%]}{100} + 2.6553\right) \cdot\ 60\ \left[\frac{€}{MWh}\right]$$	5-28

Lime consumption is calculated by equation 5-29 to estimate the demand of CaO per ton of SO_2 abated and then equation 5-31.

$$\gamma_{CaO}^{s}\left[\frac{t\ CaO}{t\ SO2\ abated}\right] = \frac{\left(6.3598\ \cdot\ \frac{\eta^{LSD}[\%]}{100} -\ 4.2339\right)}{\frac{PUR_{CaO}\ [\%]}{100}}$$	5-29
$$1.2\left[\frac{t\ CaO}{t\ SO2\ abated}\right] = \frac{\left(6.3598\ \cdot\ \frac{84.7[\%]}{100} -\ 4.2339\right)}{\frac{96\ [\%]}{100}}$$	5-29

$$C_{CaO}^{LSD}\left[\frac{€}{year}\right] = \gamma_{CaO}^{s}\left[\frac{t_{\ CaO}}{t_{\ SO2}}\right]\ \cdot m_{SO2\ abated}^{LS\ D\ FGD}\ \left[\frac{t_{\ SO2}}{year}\right] \cdot\ C_{CaO,spe}\left[\frac{€}{t_{\ CaO}}\right]$$	5-31
$$1{,}605{,}000\left[\frac{€}{year}\right] = 1.2\left[\frac{t_{\ CaO}}{t_{\ SO2}}\right]\ \cdot\ 16661\ \left[\frac{t_{\ SO2}}{year}\right] \cdot 80\left[\frac{€}{t_{\ CaO}}\right]$$	5-31

By-product production (cell D177) and costs of elimination are calculated by equation 5-32 and then by equation 5-33 to estimate annual costs.

$\gamma_{bp}^{s}\left[\frac{t_{bp}}{t_{SO2\ abated}}\right]=\ \gamma_{CaO}^{s}\left[\frac{t\ CaO}{t\ SO2}\right]\cdot\left(\frac{100-PUR_{CaO[\%]}}{100}\cdot 1+\frac{PUR_{CaO[\%]}}{100}\cdot 2.366\right)\left[\frac{t_{bp}}{t_{CaO}}\right]$	5-32
$2.783\left[\frac{t_{bp}}{t_{SO2\ abated}}\right]=\ 1.2\left[\frac{t\ CaO}{t\ SO2}\right]\cdot\left(\frac{100-96}{100}\cdot 1+\frac{96}{100}\cdot 2.366\right)\left[\frac{t_{bp}}{t_{CaO}}\right]$	5-32

$C_{bp}^{LSD}\left[\frac{€}{year}\right]=m_{SO2\ abated}^{LSD\ FGD}\left[\frac{t_{SO_2}}{year}\right]\cdot\gamma_{bp}^{s}\left[\frac{t_{bp}}{t_{SO_2 abated}}\right]\ \cdot C_{bp,spe}\left[\frac{€}{t_{bp}}\right]$	5-33
$927.460\left[\frac{€}{year}\right]=16{,}661\left[\frac{t_{SO_2}}{year}\right]\cdot 2.73\left[\frac{t_{bp}}{t_{SO_2 abated}}\right]\ \cdot 20\left[\frac{€}{t_{bp}}\right]$	5-33

Total operating costs (fixed operating costs, electricity consumption costs, reagent costs and byproduct elimination) are 7.353 M€/year (cell D181).

The total annual cost including the annual capital cost is of 19.093 M€/year (cell D189).

Cost summary

The summary of costs is as follows (cells C117 to E128):

Summary for LSD FGD : Installation 1250 MWth and 100 % load, coal S: 0.72% waf		
SO_2 emissions avoided	16 661	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	85	%
Total investment	130 534 038	€
Total annual costs	19 093 029	€/year
Spec.SO_2 reduction cost	1 146	€/t SO_2 abated
Spec. investment per kWth	104	€/kWth
Electricity penalty	1.10	%
Share capital costs to total costs	61.5%	
Share operating costs to total costs	38.5%	

If the load is 80%, the costs are as follows:

Summary for LSD FGD : 1250 MW and load 80%, coal S: 0.72% waf		
SO_2 emissions avoided	13 329	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	130 534 038	€
Total annual costs	18 010 837	€/year
Spec.SO_2 reduction cost	1 351	€/t SO_2 abated
Spec. investment per kWth	104	€/kWth
Electricity penalty	1.10	%
Share capital costs to total costs	65.19%	
Share operating costs to total costs	34.81%	

If the load is 50%, the costs are as follows:

Summary for LSD FGD : 1250 MW and load 50%, coal S: 0.72% waf		
SO_2 emissions avoided	8 331	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	130 534 038	€
Total annual costs	16 387 550	€/year
Spec.SO_2 reduction cost	1 967	€/t SO_2 abated
Spec. investment per kWth	104	€/kWth
Electricity penalty	1.10	%
Share capital costs to total costs	71.64%	
Share operating costs to total costs	28.36%	

Costs of DSI FGD

The cost estimation assumes that the existing ESP has been maintained. A new fabric filter is used for desulphurization.

Case 1

Costs are firstly calculated with the use of low sulphur fuel. The following hypothesis is taken into account (cells D35 to D39):

Primary Measures		
Do you want to use a lower sulphur content coal?	Y	Yes/No
What is the sulphur content of the coal?	0.4	% Sulphur w/w waf
Concentration achieved with low sulphur content fuel	729	mg/Nm³, ref O_2, dry
Gap-Closure to emission goal (% of Cell D7)	52.4	%
Reduction required with secondary measure	72.5	%

The use of the low sulphur fuel with S concentration of 0.4 % waf (compared to 0.72 % waf) enables to abate SO_2 emissions from 1311 mg/Nm³, ref O_2, dry to 729 mg/Nm³, ref O_2, dry. The efficiency is not sufficient to reach the target of 200 mg/Nm^3. A secondary measure is used, based on DSI FGD. Its minimum efficiency has to be 72.5%.

Secondary Measures		
Inlet SO2 concentrations	729	mg/Nm³, ref O_2, dry
Do you want to estimate costs for LSFO FGD?	N	Yes/No
Do you want to estimate costs for LSD FGD?	N	Yes/No
Do you want to estimate costs for DSI FGD?	Y	Yes/No
New SO_2 outlet emissions	200	mg/Nm³, ref O_2, dry
Total reduction required	72.5	%
Degree of Over-Achievement to ELV	0	%
Retrofit factor	1	
Coal factor	1	

Low sulphur fuel costs:

SO_2 abated and additional costs for low sulphur fuels are as follows (cells D73 to D80):

Primary Measures - Low sulphur fuels		
SO_2 emissions saved	8 758.2	t SO_2/year
Spec. Additional cost of low sulphur coal	5.0	€/t coal
Total Investment	No investment	€
Capital Cost p.a.	No capital cost	€/year
Annual additional costs	8 782 058	€/year
Total annual costs	**8 782 058**	**€/year**
spec. SO_2 reduction costs	**1 005**	**€/t SO2**

The mass of SO_2 abated is calculated by equation 5-45:

$m_{SO2\ abated}^{low\ sulphur\ fuel}\left[\frac{t\ _{SO2}}{year}\right]=\left(load_{SO2,fuel\ 1}\left[\frac{kg_{SO2}}{GJ}\right]-load_{SO2,fuel\ 2}\left[\frac{kg_{SO2}}{GJ}\right]\right)\cdot cons_e^{fuel}\left[\frac{GJ}{h}\right]\cdot cap\frac{[\%]}{100}\cdot 8{,}760\ .\ 0.001\left[\frac{t}{kg}\right]$	5-45

Fuel 1 is the fuel replaced with S at 0.72 % waf and fuel 2 is the new fuel with S at 0.4 % waf.

$8758\ \left[\frac{t\ _{SO2}abated}{year}\right]=\left(0.499\left[\frac{kg_{SO2}}{GJ}\right]-0.277\left[\frac{kg_{SO2}}{GJ}\right]\right)\cdot 4500\left[\frac{GJ}{h}\right].\frac{100[\%]}{100}\cdot 8{,}760\ .\ 0.001\left[\frac{t}{kg}\right]$	5-45

Annual costs are due to additional cost of the low sulphur fuel, assumed to be 5 €/t:

$C^{low\ sulphur\ fuel}\ \left[\frac{€}{year}\right]=cons_e^{fuel}\left[\frac{t\ coal}{h}\right]\cdot cap\frac{[\%]}{100}\cdot 8{,}760\ \cdot\ C_{low\ S\ fuel,spe}^{additional}\left[\frac{€}{tcoal}\right]$	5-46
$8{,}782{,}000\ \left[\frac{€}{year}\right]=201\left[\frac{t\ coal}{h}\right]\cdot\frac{100[\%]}{100}\cdot 8{,}760\ \cdot\ 5\left[\frac{€}{tcoal}\right]$	5-46

DSI FGD costs

Secondary Measures - DSI FGD		
DSI FGD (Y/N)	Y	Y/N
SO_2 emissions saved	7 924	t SO_2/year
Is there valorisation of waste	Y	y/n
Capital Costs		
PJFF	*61 626 454*	€
Reagent preparation unit, injection device unit cost	*18 487 936*	€
Total investment for DSI FGD	**80 114 390**	**€**
Capital Cost p.a.	**7 205 576**	**€/year**

The quantity of SO_2 abated is derived from equation 5-12:

$m_{SO2\ abated}^{LSFO\ FGD}\ \left[\frac{t\ _{SO2}}{year}\right]=\left(c_{SO2,in}\left[\frac{mg}{Nm^3}\right]-c_{SO2,load\ emit}\left[\frac{mg}{Nm^3}\right]\right)\cdot\frac{1}{f_{O2,corr}}\cdot\dot{v}_{dry,year}^{flue\ gas}\left[\frac{Nm^3}{year}\right]\cdot 10^{-9}\left[\frac{t}{mg}\right]$	5-12
$m_{SO2\ abated}^{LSFO\ FGD}\ \left[\frac{t\ _{SO2}}{year}\right]=\left(729\left[\frac{mg}{Nm^3}\right]-200\left[\frac{mg}{Nm^3}\right]\right)\cdot\frac{1}{0.87}\cdot 13{,}058{,}023{,}445\left[\frac{Nm^3}{year}\right]\cdot 10^{-9}\left[\frac{t}{mg}\right]$	5-12

The quantity of SO_2 abated can also be derived from equation 5-2bis providing the SO_2 load per GJ, the fuel consumption expressed in GJ and the efficiency required for FGD (equation 5.12bis):

$load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right] = \frac{\frac{M_{SO2}\left[\frac{kg}{kmol}\right]}{Ms\left[\frac{kg}{kmol}\right]} \cdot x_S[waf\%] \cdot 10\left[\frac{kg\,S}{kg\,fuel}\right] \cdot \left[\frac{100 - x_{ash\,[\%]} - x_{moist}[\%]}{10000}\right] \cdot \left[\frac{100 - x_{S\,retainedinbo}[\%]}{100}\right]}{LHV^{fuel}\left[\frac{MJ}{kg\,fuel}\right]} \cdot 1000\left[\frac{MJ}{GJ}\right]$	5-2 bis
$0.277\left[\frac{kg_{SO2}}{GJ}\right] = \frac{\frac{64\left[\frac{kg}{kmol}\right]}{32\left[\frac{kg}{kmol}\right]} \cdot 0.4[waf\%] \cdot 10\left[\frac{kg\,S}{kg\,fuel}\right] \cdot \left[\frac{100 - 14.49 - 7.71}{10000}\right] \cdot \left[\frac{100 - 0}{100}\right]}{22.44\left[\frac{MJ}{kg\,fuel}\right]} \cdot 1000\left[\frac{MJ}{GJ}\right]$	5-2 bis

$m_{SO2\,abated}^{LSFO\,FGD}\left[\frac{t_{SO2}}{year}\right] = \left(load_{SO2}\left[\frac{kg_{SO2}}{GJ}\right] \cdot cons_e^{fuel}\left[\frac{GJ}{h}\right] \cdot cap\frac{[\%]}{100} \cdot 8{,}760\right) \cdot 0.001\left[\frac{t}{kg}\right] \cdot \frac{\eta^{LSFO}}{100}$	5-12bis
$7924\left[\frac{t_{SO2}}{year}\right] = \left(0.277\left[\frac{kg_{SO2}}{GJ}\right] \cdot 4500\left[\frac{GJ}{h}\right] \cdot \frac{100[\%]}{100} \cdot 8{,}760\right) \cdot 0.001 \cdot 72.5/100$	5-12bis

For operating costs, it is assumed that by-products are valorised in cement industry as fly ashes are not present (presence of the ESP). However in cell D213 "N" is input due to the fact that costs are encountered and no benefits are obtained (According to a plant operator, costs for disposal of powder products are large (about 200 €/t). Even if products are valorised in a cement plant, costs are encountered (40 €/t)).

PJFF investment and operating costs depend on the bp concentration to be abated.

The bp load is calculated as follows:

The demand of CaO is estimated:

$\gamma_{CaO}^{S}\left[\frac{t\,CaO}{t\,SO2\,abated}\right] = \frac{\left(6.5625 \cdot \frac{\eta^{DSI}[\%]}{100} - 1.2396\right)}{\frac{PUR_{CaO}\,[\%]}{100}}$	5-38
$3.67\left[\frac{t\,CaO}{t\,SO2\,abated}\right] = \frac{\left(6.5625 \cdot \frac{72.5[\%]}{100} - 1.2396\right)}{\frac{96\,[\%]}{100}}$	5-38

The production of by-product is estimated:

$\gamma_{bp}^{S}\left[\frac{t_{bp}}{t_{SO2\,abated}}\right] = \gamma_{CaO}^{S}\left[\frac{t\,CaO}{t\,SO2}\right] \cdot \left(\frac{100 - PUR_{CaO[\%]}}{100} \cdot 1 + \frac{PUR_{CaO[\%]}}{100} \cdot 2.366\right)\left[\frac{t_{bp}}{t_{CaO}}\right]$	5-39
$8.479\left[\frac{t_{bp}}{t_{SO2\,abated}}\right] = 3.67\left[\frac{t\,CaO}{t\,SO2}\right] \cdot \left(\frac{100 - 96}{100} \cdot 1 + \frac{96}{100} \cdot 2.366\right)\left[\frac{t_{bp}}{t_{CaO}}\right]$	5-39

The concentration at the PJFF inlet is calculated:

$$load_{bp,dry,in,\lambda}^{DSI\ FGD}\left[\frac{mg}{Nm3}\right]=\frac{m_{SO2\ abated}^{DSI\ FGD}\left[\frac{t_{\ SO2}}{year}\right]\cdot\gamma_{bp}^{S}\left[\frac{t\ bp}{t\ SO2\ abated}\right]}{\dot{v}_{\lambda,dry,year}^{flue\ gas}\left[\frac{Nm^3}{year}\right]}\cdot 10^9\ [\frac{mg}{t}]$$	5-40
$$5.145\left[\frac{mg}{Nm3}\right]=\frac{7924\quad\left[\frac{t_{\ SO2}}{year}\right]\cdot 8.479\left[\frac{t\ bp}{t\ SO2\ abated}\right]}{13{,}058{,}023{,}445\left[\frac{Nm^3}{year}\right]}\cdot 10^9\ [\frac{mg}{t}]$$	5-40

$$load_{bp,dry,in,ref O2}^{DSI\ FGD}\left[\frac{mg}{Nm3}\right]=load_{bp,dry,in,\lambda}^{DSI\ FGD}\left[\frac{mg}{Nm3}\right]\cdot f_{O2,corr}$$	5-40 Bis
$$4{,}482\left[\frac{mg}{Nm3}\right]=5{,}145\left[\frac{mg}{Nm3}\right]\cdot\ 0.87$$	5-40 Bis

Investment in PJFF is calculated in sheet “Solid fuel_Fabric_Filter DSI”. Input data are as follows. The concentration of bp to be abated is automatically filled. The target has been fixed to 10 mg/Nm³, O_2ref, dry (cell D12).

Which Dust emission goal (at stack) do you want to achieve?		
Dust stack emission	10.0	mg/Nm³, O_2ref, dry
Current %-Gap to goal	99.71	%
Dust inlet concentration	4482	mg/Nm³, O_2ref, dry

The air to cloth ratio is fixed in the EXCEL tool to a lower range for a longer residence time to enable the desulphurisation to be as effective as possible.

Investments are as follows (sheet “Solid fuel_Fabric_Filter DSI”, cells C78 to E83):

Economic Analysis		
By-product emissions avoided	67 031.4	t bp/year
Equipment cost	23 793 998	€
Direct installation cost	17 607 558	€
Indirect installation cost	10 707 299	€
Is it a new PJFF unit?	N	Y/N
Total Investment	**61 626 454**	**€**

The reagent preparation unit, injection device unit costs are assumed to be 30% of the PJFF investment or 18.5 M€.

Operating costs (sheet “Solid fuels_DeSO2”, cells C223 to E 242)**:**

	Operating Costs	
Fixed O&M Costs	1 602 288	€/year
Reagent price	*80*	*€ / ton CaO*
Specific limestone demand	*3.67*	*t CaO/t SO_2*
Reagent consumption	*29 066*	*t CaO/year*
Reagent cost	2 325 258	€/year
Electricity price	*60.000*	*€/MWh*
Electricity consumption	*37 557*	*MWh/year*
Electricity cost (PJFF)	2 253 411	€/year
By-product price	40.00	*€ / ton By-product*
By-product generated	8.479	*t By-product/t SO_2 abated*
By-product amount	67 181	*t By-product produced/year*
By-product amount recovered with PJFF	67 031	*t By-product recovered/year*
By-product concentration (inlet FF)	4 482	*mg by-product/Nm3, dry, $refO_2$*
By-product management cost	2 681 258	€/year
Bag replacement cost	1 835 123	€/year
Annual operating costs	**10 697 338**	**€/year**

The fixed operating costs are calculated with a ratio of 2 % of the investment.

The percentage is applied on the equipment investment: 2 /100 x 80.1 or 1.6 M€/year.

Lime demand is calculated by equation 5-38 presented above.

Cost of lime consumption is provided by equation 5-42:

$C_{CaO}^{DSI}\left[\frac{€}{year}\right] = \gamma_{CaO}^{S}\left[\frac{t\ _{CaO}}{t\ _{SO2\ abated}}\right] \cdot m_{SO2\ abated}^{DSI\ FGD}\left[\frac{t\ _{SO2}}{year}\right] \cdot C_{CaO,spe}\left[\frac{€}{t\ _{CaO}}\right]$	5-38
$2{,}325{,}258\left[\frac{€}{year}\right] = 3.67\left[\frac{t\ _{CaO}}{t\ _{SO2\ abated}}\right] \cdot 7924\left[\frac{t\ _{SO2}}{year}\right] \cdot 80\left[\frac{€}{t\ _{CaO}}\right]$	5-38

By-product production (cell D236) is 5-39 presented above. Cost of by-product elimination is provided by equation 5-43 and 5-44:

$m_{bp,abated,PJFF}\left[\frac{t_{bp}}{year}\right] = \left(load_{bp,dry,O2ref}\left[\frac{mg}{Nm^3}\right] - c_{bp,load\ emit,refO2}\left[\frac{mg}{Nm^3}\right]\right) \cdot \frac{1}{f_{O2,corr}} \cdot \dot{v}_{\lambda,dry,year}^{flue\ gas}\left[\frac{Nm^3}{year}\right] \cdot 10^{-9}$	5-43
$67{,}031\left[\frac{t_{bp}}{year}\right] = \left(4482\left[\frac{mg}{Nm^3}\right] - 10\left[\frac{mg}{Nm^3}\right]\right) \cdot \frac{1}{0.87} \cdot 13{,}058{,}023{,}445\left[\frac{Nm^3}{year}\right] \cdot 10^{-9}$	5-43

Annual costs are defined according to equation 5-44:

$C_{bp}^{PJFF}\left[\frac{€}{year}\right]=\left(m_{bp,abated,PJFF}\left[\frac{t_{bp}}{year}\right]\cdot C_{bp,spe}\left[\frac{€}{t_{bp}}\right]\right)$	5-44
$2{,}681{,}258\left[\frac{€}{year}\right]=\left(67{,}031\left[\frac{t_{bp}}{year}\right]\cdot 40\left[\frac{€}{t_{bp}}\right]\right)$	5-44

Electricity consumption is defined according to equations 1-6 and 4-11:

$cons_{elec}^{fan}\left[\frac{MWh}{year}\right]=2{,}764.10^{-8}\cdot\frac{\dot{v}_{\lambda,wet,year}^{flue\ gas}\left[\frac{Nm^3}{year}\right]\cdot\Delta P[mbar]}{\eta_{fan}[\%]}$	5-12
$27763\left[\frac{MWh}{year}\right]=2{,}764.10^{-8}\cdot\frac{1.395\ 10^{10}\left[\frac{Nm^3}{year}\right]\cdot 50[mbar]}{65[\%]}$	5-12

$cons_{ut.elec}^{air\ comp}\left[\frac{MWh}{h}\right]=0.000375\cdot\dot{v}_{\lambda,dry,s}^{flue\ gas}\left[\frac{Nm^3}{s}\right]\cdot{}^{c}/_{a}\cdot 3600$	4-11

The annual consumption for compressed air is 9793 MWh. The total electricity consumption is 37556 MWh.

The consumption is multiplied by 60 €/MWh to obtain 2.253 M€/year.

Bag replacement costs are estimated by:

$C_{rep}^{bag}\left[\frac{€}{year}\right]=\frac{(1+p[\%])^{n^{bag}}}{(1+p[\%])^{n^{bag-1}}}\cdot p[\%]\cdot\left(C^{bag}[€]+2{,}15\cdot A_{GC}[m^2]\right)$	5-14

With bag lifetime of 20,000 hours and hypothesis for PJFF configuration (number of cage, number of bags…), costs are 1.835M€/year.

Total operating costs (fixed operating costs, electricity consumption costs, reagent costs and byproduct elimination) are 10.697 M€/year.

The total annual cost including annual capital cost is 17.902 M€/year.

The summary of costs is as follows (cells C244 to E268):

For 100 % load:

Summary for DSI FGD : Installation 1250 MWth and 100 % load, coal S: 0.72% waf replaced by a 0.4%		
SO_2 emissions avoided	7 924	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	729	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	72.5	%
Total investment	80 114 390	€
Total annual costs	17 902 914	€/year
Spec.SO_2 reduction cost	2 259	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	40.3%	
Share operating costs to total costs	59.7%	

Adding costs of low sulphur fuel, the balance is as follows:

Summary for low sulphur fuel and DSI FGD and 100 % load, coal S: 0.72% waf replaced by a 0.4%		
SO_2 emissions avoided	16 661	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	80 114 390	€
Total annual costs	26 684 972	€/year
Spec.SO_2 reduction cost	1 602	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	27.0%	
Share operating costs to total costs	73.0%	

For 80 % load:

Summary for DSI FGD : Installation 1250 MWth and 80% load, coal S: 0.72% waf replaced by a 0.4%		
SO_2 emissions avoided	6 339	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	729	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	72.5	%
Total investment	80 114 390	€
Total annual costs	16 100 150	€/year
Spec.SO_2 reduction cost	2 540	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	44.8%	
Share operating costs to total costs	55.2%	

Adding costs of low sulphur fuel, the balance is as follows:

Summary for low sulphur fuel and DSI FGD and 80% load, coal S: 0.72% waf replaced by a 0.4%		
SO_2 emissions avoided	13 329	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	80 114 390	€
Total annual costs	23 125 796	€/year
Spec.SO_2 reduction cost	1 735	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	31.2%	
Share operating costs to total costs	68.8%	

For 50 % load:

Summary for DSI FGD : Installation 1250 MWth and 50% load, coal S: 0.72% waf replaced by a 0.4%		
SO_2 emissions avoided	3 962	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	729	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	72.5	%
Total investment	80 114 390	€
Total annual costs	13 396 443	€/year
Spec.SO_2 reduction cost	3 381	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	53.8%	
Share operating costs to total costs	46.2%	

Adding costs of low sulphur fuel, the balance is as follows:

Summary for low sulphur fuel and DSI FGD and 50 % load, coal S: 0.72% waf replaced by a 0.4%		
SO_2 emissions avoided	8 331	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	80 114 390	€
Total annual costs	17 787 390	€/year
Spec.SO_2 reduction cost	2 135	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	40.5%	
Share operating costs to total costs	59.5%	

Case 2

Costs can also be calculated without the use of low sulphur fuel, however the required efficiency of 85 % is higher than the range of use of the technique (50 to 80%). The following hypothesis is taken into account (cells D35 to D39):

Primary Measures		
Do you want to use a lower sulphur content coal?	N	Yes/No
What is the sulphur content of the coal?	0.4	% Sulphur w/w waf
Concentration achieved with low sulphur content fuel	Not valid	mg/Nm³, ref O_2, dry
Gap-Closure to emission goal (% of Cell D7)	n/a	%
Reduction required with secondary measure	84.75	%

The efficiency required is at the maximum capacity of DSI FGD.

Secondary Measures		
Inlet SO2 concentrations	1311.5	mg/Nm³, ref O_2, dry
Do you want to estimate costs for LSFO FGD?	Y	Yes/No
Do you want to estimate costs for LSD FGD?	Y	Yes/No
Do you want to estimate costs for DSI FGD?	Y	Yes/No
New SO_2 outlet emissions	200	mg/Nm³, ref O_2, dry
Total reduction required	84.75	%
Degree of Over-Achievement to ELV	0	%
Retrofit factor	1	
Coal factor	1	

For 100 % load:

Summary for DSI FGD : Installation 1250 MWth and 100 % load, coal S: 0.72% waf		
SO_2 emissions avoided	16 661	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	80 114 390	€
Total annual costs	25 826 421	€/year
Spec.SO_2 reduction cost	1 550	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	27.9%	
Share operating costs to total costs	72.1%	

For 80 % load:

Summary for DSI FGD : Installation 1250 MWth and 80% load, coal S: 0.72% waf		
SO_2 emissions avoided	13 329	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	80 114 390	€
Total annual costs	22 438 956	€/year
Spec.SO_2 reduction cost	1 683	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	32.1%	
Share operating costs to total costs	67.9%	

For 50 % load:

Summary for DSI FGD : Installation 1250 MWth and 50% load, coal S: 0.72% waf		
SO_2 emissions avoided	8 331	t SO_2/year
Outlet SO_2 concentrations	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	80 114 390	€
Total annual costs	17 358 197	€/year
Spec.SO_2 reduction cost	2 084	€/t SO_2 abated
Spec. investment per kWth	64	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	41.5%	
Share operating costs to total costs	58.5%	

Summary for the plant of 1250 MWth

The following comparison can be done for the 1250 MW plant, coal with 0.72%S and 80% load.

	LSFO FGD	LSD FGD	DSI FGD	DSI FGD + low sulphur coal (+5 €/t coal)	t SO_2/year
SO_2 emissions avoided	13 329	13 329	13 329	13 329	t SO_2/year
Outlet SO_2 concentrations	200	200	200	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	1 311	1 311	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	84.7	84.7	84.7	%
Total investment	145 109 924	130 534 038	80 114 390	80 114 390	€
Total annual costs	18 610 145	18 010 837	22 438 956	23 125 796	€/year
Spec.SO_2 reduction cost	1 396	1 351	1 683	1 735	€/t SO_2 abated
Spec. investment per kWth	116	104	64	64	€/kWth
Electricity penalty	1.39	1.10	0.86	0.86	%
Share capital costs to total costs	70.1%	65.19%	32.1%	31.2%	
Share operating costs to total costs	29.9%	34.81%	67.9%	68.8%	

Additional example

An example is developed for a unit of 80 MW, using the same coal and with a load of 80%. The results are as follows assuming a modular PJFF:

Summary for DSI FGD : Installation 80 MWth and 80% load, coal S: 0.72% waf		
SO_2 emissions avoided	853	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	9 557 470	€
Total annual costs	1 935 270	€/year
Spec.SO_2 reduction cost	2 267	€/t SO_2 abated
Spec. investment per kWth	119	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	44.4%	
Share operating costs to total costs	55.6%	

In the case above a modular pulse jet is used. If a field assembled PJFF is used, costs are increased as follows:

Summary for DSI FGD : Installation 80 MWth and 80% load, coal S: 0.72% waf		
SO_2 emissions avoided	853	t SO_2/year
Outlet SO_2 concentrations obtained	200	mg/Nm³ SO_2, dry, ref O_2
Inlet SO_2 concentrations	1 311	mg/Nm³ SO_2, dry, ref O_2
Efficiency required	84.7	%
Total investment	29 353 314	€
Total annual costs	4 111 434	€/year
Spec.SO_2 reduction cost	4 820	€/t SO_2 abated
Spec. investment per kWth	367	€/kWth
Electricity penalty	0.86	%
Share capital costs to total costs	64.2%	
Share operating costs to total costs	35.8%	

Fabric filter (Sheet solid fuels_fabric_filter)

Characteristics of the fabric filter are determined.

Which Dust emission goal (at stack) do you want to achieve?		
Dust stack emission to be obtained	20.0	mg/Nm³,02 ref
Current %-Gap to goal	99.88	%
Inlet dust concentration	16 458	mg/Nm³,02 ref

Air to cloth ratio for pulse jet fabric filter		
Air to cloth ratio [A/C]	1,30E-02	m/s
Volumetric gas flow [vflue gas,λ,dry]	414	Nm³ Flue Gas,dry,λ / s
Net cloth area [A_{NC}]	31 852	m2
Gross cloth area [A_{GC}]	33 127	m2

Air-to-Cloth values are calculated according to equation 4-1. The G/C ratio ranges between 1.00 10^{-2} and 2.33 10^{-2} m/s (ref. Box 1). 1.3 10^{-2} m/s is selected for the case study.

The Net Cloth Area is calculated through equation 4-1.

$$A_{NC}[m^2] = \frac{\dot{v}_{\lambda,dry,sec}^{flue\ gas}\left[\frac{Nm^3}{s}\right]}{G/C\ \left[\frac{m}{s}\right]}$$	4-1
$$31852[m^2] = \frac{414\left[\frac{Nm^3}{s}\right]}{0.013\ \left[\frac{m}{s}\right]}$$	4-1

The Gross Cloth Area A_{GC} is calculated by f^{N-G} following equation 4-2:

$$A_{GC}[m^2] = A_{NC}[m^2] \cdot f^{N-G}$$	4-2

For A_{NC}= 31852 m^2, f^{N-G}equal 1.04 (Reference box PJFF2)

$$33127[m^2] = 31852[m^2] \cdot 1.04$$	4-2

The number of compartment is fixed to 8 (range from 1 to 30, reference box PJFF3) and the number of extra compartments to 2 (range from 0 to 2, reference box PJFF3). The compartment surface is:

$$A_{comp}[m^2] = \frac{A_{GC}[m^2]}{nb_{comp}}$$	4-3
$$4141[m^2] = \frac{33127[m^2]}{8}$$	4-3

$$A_{tot}[m^2] = A_{GC}[m^2] + A_{comp}[m^2] \cdot nb_{extra-comp}$$	4-4
$$41409[m^2] = 33127[m^2] + 4141[m^2] \cdot 2$$	4-4

Cost of the baghouse compartments is as follows, when stainless steel and thermal insulation are selected. Filed assembled unit option is chosen because total cloth area A_{tot} exceed 2000 m² (when A_{tot} is below 2000 m^2, the operator can choose between Pre or Field assembled unit).

Cost for baghouse compartments		
Compartment Area [A_{comp}]	4 141	m2
Baghouse type	Field assembled units	
Basic unit	Y	Y
Stainless Steel	Y	Y/N
Thermal insulation	Y	Y/N
a1	422 647	€
a2	143 808	€
a3	89 879	€
b1	90	€/m2
b2	34	€/m2
b3	10	€/m2
Cost for baghouse compartments	12 099 742	€

$$12{,}099{,}742[€] = \big((422647 + 143808 + 89879)[€] + (90 + 34 + 10).4141 \ \ [m^2]\big) \cdot (8 + 2)$$	

Cost of bags is as follows when RT and 9 €/m^2 for the reference price are selected.

Bags cost		
Media material	RT	
Reference price for PE material	9	€/m2
Bag prices [C^{bag}_{area}]	56.25	€/m2
Bags cost [C^{bag}_{total}]	2 329 242	€

$$2{,}329{,}242[€] = 41409\ [m^2] \cdot 9[€] \ \cdot \ 6.25 \left[\frac{RT}{PE}\ from\ ref\ box\ 5\right]$$	4-6

Cage cost is as follows with a price of cage of 20 €/m^2 of filtering media area (range of 16 to 25 €/m^2, reference box PJFF6):

Cage cost for pulse jet application		
Lenght	8	M
Diameter	150	Mm
Cage price per m^2 of filtering media area	20.00	€/m^2
Total cage cost	828 175	€

$$828{,}175[€] = 41{,}409\ [m^2] \cdot 20\ [€/m^2]$$

The total costs for the PJFF are as follows:

Economic Analysis		
Dust emissions avoided	246 413,3	t/a
Equipment cost	17 545 733	€
Direct installation cost	12 983 842	€
Indirect installation cost	7 895 580	€
Is it a new PJFF unit?	N	Y/N
Is there valorisation of by-products?	Y	Y/N
Total Investment	**45 443 449**	**€**
Capital Cost p.a.	4 087 233.8	€/a

Dust emissions avoided are estimated by equation 4-13:

$$246\ 413\left[\frac{t_{ash}}{year}\right] = \left(16458\left[\frac{mg}{Nm^3}\right] - 20\left[\frac{mg}{Nm^3}\right]\right) \cdot \frac{1}{0.87} \cdot 13{,}058{,}023{,}445\left[\frac{Nm^3}{year}\right] \cdot 10^{-9} \quad \text{4-13}$$

Equipment cost is derived by equation 4-7:

$$C_{equip}^{PJFF}[€] = f^{inst} \cdot \left(C^{baghouse}[€] + C_{tot}^{bag}[€] + C_{tot}^{cage}[€]\right) \quad \text{4-7}$$

$$C_{equip}^{PJFF}[€] = 1.15 \cdot \left(12{,}099{,}742[€] + 2{,}329{,}242[€] + 828{,}175\ \ [€]\right) \quad \text{4-7}$$

The direct installation cost and the indirect installation cost are derived using the factors of 0.74 and 0.45 respectively (equation 4-8 to 4-9).

For an existing installation, the total cost is derived as follows:

$$C_{inv}^{PJFF}[€] = 1.4\ \cdot C_{equip}^{PJFF}[€] + C_{inst}^{direct}[€] + C_{inst}^{indirect}[€] \quad \text{4-10}$$

$$45{,}443{,}449[€] = 1.4\ \cdot\ 17{,}515{,}733[€] + 12{,}983{,}842[€] + 7{,}895{,}580[€] \quad \text{4-10}$$

Operating costs

Operating costs are as follows:

Operating Costs		
Fixed O&M Costs	**908 869**	**€/a**
Variable Operating Costs		
Pressure drop value	50	mbar
Fan efficiency	65%	%
Fan utility electricity consumption	3.169	MWh/h
Compressed to actual air flow ratio	0.002	
Air compressor consumption	1.12	MWh/h
Bag-life	20000	hours
By-Product management cost	**-246 413**	**€/a**
Utility electricity cost	**2 253 411**	**€/a**
Bag replacement cost [C_{rep}^{bags}]	**1 129 335**	**€/a**

Fixed operating costs are 2% of the total investment.

Electricity demand for fans is as follows (equation 1-6 adapted):

$cons_{elec}^{fan}\left[\frac{MWh}{h}\right] = 2.76 \cdot 10^{-8} \cdot \frac{\dot{v}_{\lambda,dry,s}^{flue\ gas}\left[\frac{Nm^3}{s}\right] \cdot \Delta P[mbar] \cdot 3{,}600}{\eta_{fan}[\%]}$	1-6
$3.169\left[\frac{MWh}{h}\right] = 2.76 \cdot 10^{-8} \cdot \frac{414\left[\frac{Nm^3}{s}\right] \cdot 50[mbar] \cdot 3{,}600}{65/100[\%]}$	1-6

Electricity demand for compressed air is as follows:

$cons_{ut.elec}^{air\ comp}\left[\frac{MWh}{h}\right] = 0.000375 \cdot \dot{v}_{\lambda,dry,s}^{flue\ gas}\left[\frac{Nm^3}{s}\right] \cdot {}^{c}/_{a} \cdot 3{,}600$	4-11
$1.12\left[\frac{MWh}{h}\right] = 0.000375 \cdot 414\left[\frac{Nm^3}{s}\right] \cdot 0.002 \cdot 3600$	4-11

The total consumption depends on the capacity factor. Electricity price of 60 €/MWh is used to derived the total annual cost of electricity of 2,253,411 €/year.

Bag replacement costs are as follows (assuming 20,000 hours lifetime):

$C_{rep}^{bag}\left[\frac{€}{year}\right] = \frac{(1+p[\%])^{n_{bag}}}{(1+p[\%])^{n_{bag}-1}} \cdot p[\%] \cdot \left(C^{bag}[€] + 2{,}15 \cdot A_{tot}[m^2]\right)$	4-12
$1{,}129{,}335\left[\frac{€}{year}\right] = \frac{(1+4/100[\%])^{20000/8760}}{(1+4/100[\%])^{20000/8760-1}} \cdot 4/100[\%] \cdot \left(\begin{matrix}2{,}329{,}242[€] + 2{,}15 \cdot \\ 41{,}409[m^2]\end{matrix}\right)$	4-12

By-products are assumed to be valorised in cement plants for a price of 1 €/t bp.

Byproducts management costs are consequently -246,413 €/year.

The summary is as follows for PJFF on a 1250 MWth plant using coal with 14.5% ash.

	100% load	80% load	50% load	
TSP emissions avoided	246 413	197 131	123 207	t TSP/year
inlet TSP concentrations	16 458	16 458	16 458	mg/Nm³ TSP, dry, ref O_2-%
outlet TSP concentrations	20	20	20	mg/Nm³ TSP, ref O_2-%
Efficiency required	99,88	99,88	99,88	%
Total investment	45 443 449	45 443 449	45 443 449	€
Total annual costs	8 132 436	7 515 167	6 589 534	€/year
Spec.TSP reduction cost	33	38	53	€/t TSP abated
Spec. investment per kWth	36	36	36	€/kWth
Electricity penalty	0,86	0,86	0,86	%
Share capital costs to total costs	50,3%	54,4%	62,0%	
Share operating costs to total costs	49,7%	45,6%	38,0%	

ESP (sheet solid fuel_ESP)

The first steps are the calculation of the effective collecting plate area with equation 4-15 to 4-26. Hypothesis are a temperature of 400 K and a mass mean diameter of 20 µm.

Method for A ECP determination		
Back corona	N	Y/N
Temperature [T]	400,0	K
Mass mean Diameter [MMDin]	20	µm
Design penetration	0.0012	
Gas viscosity [μ_G]	2.26E-05	kg/m/s
Electric field at sparking [Ebd]	3.35E+05	V/m
E avg	1.92E+05	V/m
n	5	
Average section penetration [ps]	0.26	
Section collection penetration [pc]	0.08	
D	0.26	
MMDrp	2.30	µm
[SCA]	136.73	s/m
dry flue gas volume per second [$v^{flue\ gas}_{\lambda,dry,sec}$]	414	Nm³ Flue Gas,dry,λ /sec
Effective Collecting Plate Area [A_{ECP}]	**56 617**	**m2**

Investment

The equipment investment is calculated by equation 4-27.

$$C^{ESP,equip}[€] = a \cdot (A_{ECP}[m^2])^b \qquad \text{4-27}$$

a and b are provided by ref. box ESP2 for an A_{ECP} larger than 4645 m^2 and taking into account all options.

$$8{,}094{,}862[€] = 796 \cdot (56{,}617[m^2])^{0.8431} \qquad \text{4-27}$$

The ESP is selected in stainless steel 304, with a ratio of 1.3 compared to the basic unit provided in equation 4-27. An investment due to the use of SO_3 is added corresponding to 1600 . bs [MWth] or 2 M€. The total is multiplied by a factor 1.15 taking into account instrumentation.

$$14{,}401{,}820[€] = 1.15 \cdot (8{,}094{,}862[€] \cdot 1.3 + 2{,}000{,}000) \qquad \text{4-28}$$

The direct (0.67) and indirect (0.57) installation costs are added as well the fact that it is an existing plant, to obtain:

$$38{,}020{,}805[€] = 14{,}401{,}820 \ \cdot 1.4 \ [€] + C_{inst}^{direct} 9{,}649{,}219[€] + 8{,}209{,}037[€] \qquad \text{4-28 four}$$

Operating costs:

Variable operating costs are linked to electricity, SO3 consumption and by-product management.

Fixed operating costs are 2% of the total investment or 760,416 €/year.

Electricity demand for fans is as follows (equation 1-6 adapted):

$cons_{elec}^{fan}\left[\frac{MWh}{h}\right] = 2.76 \cdot 10^{-8} \cdot \frac{\dot{v}_{\lambda,dry,s}^{flue\ gas}\left[\frac{Nm^3}{s}\right] \cdot \Delta P[mbar] \cdot 3{,}600}{\eta_{fan}[\%]}$	1-6
$1.585\left[\frac{MWh}{h}\right] = 2.76 \cdot 10^{-8} \cdot \frac{414\left[\frac{Nm^3}{s}\right] \cdot 25[mbar] \cdot 3{,}600}{65/100[\%]}$	1-6

Electricity demand for the ESP itself is as follows:

$P^{ESP}\left[\frac{MWh}{h}\right] = 2.09 \cdot 10^{-5} \cdot A_{ECP}[m^2]$	4-29
$1.183\left[\frac{MWh}{h}\right] = 2.09 \cdot 10^{-5} \cdot 56{,}617 \quad [m^2]$	4-29

The total consumption depends on the capacity factor. Electricity price of 60 €/MWh is used to derived the total annual cost of electricity of 1,454,840 €/year.

By-products are assumed to be valorised in cement plants for a price of 1 €/t bp.

Byproducts management costs are consequently -246,413 €/year.

SO3 consumption is as follows with an average consumption of 35 kg/h.

$C_{SO_3}\left[\frac{€}{year}\right] = \frac{Q_{SO_3}\left[\frac{kg}{h}\right]}{1000} \cdot \frac{CAP}{100} \cdot 8{,}760\left[\frac{h}{ayear}\right] \cdot C_{SO_3,m}\left[\frac{€}{t}\right]$	4-30
$21{,}462\left[\frac{€}{year}\right] = \frac{35\left[\frac{kg}{h}\right]}{1000} \cdot \frac{100}{100} \cdot 8{,}760\left[\frac{h}{ayear}\right] \cdot 70\left[\frac{€}{t}\right]$	4-30

The summary is as follows for an ESP on a 1250 MWth plant using coal with 14.5% ash.

	100% load	80% load	50% load	
TSP emissions avoided	246 413	197 131	123 207	t TSP/year
inlet TSP concentrations	16 458	16 458	16 458	mg/Nm³ TSP, dry, ref O_2-%
outlet TSP concentrations	20	20	20	mg/Nm³ TSP, ref O_2-%
Efficiency required	99.88	99.88	99.88	%
Total investment	38 020 805	38 020 805	38 020 805	€
Total annual costs	5 409 937	5 163 960	4 794 993	€/year
Spec.TSP reduction cost	22	26	39	€/t TSP abated
Spec. investment per kWth	30	30	30	€/kWth
Electricity penalty	0.32	0.32	0.32	%
Share capital costs to total costs	63.2%	66.2%	71.3%	
Share operating costs to total costs	36.8%	33.8%	28.7%	