Convention on Long Range Transboundary Air pollution

Cooperation with the Coordinating Group on the promotion of actions towards implementation of the Convention in Eastern Europe, the Caucasus and Central Asia

APATITY COMBUSTION PLANT SO_2, NOx AND TSP EMISSION REDUCTION COST ASSESSMENT

PROVISIONAL REPORT

Prepared by EGTEI

November 2011

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1 INTRODUCTION

In the scope of the cooperation with the Coordinating Group on the promotion of actions towards implementation of the Convention in Eastern Europe, the Caucasus and Central Asia (Coordinating Group for Eastern Europe, the Caucasus and Central Asia) led by the Russian Federation (the Scientific Research Institute for Atmospheric Air Protection SRI insuring the coordination of the group) [1], EGTEI contributes to the following studies or actions:

- Carry out a pilot study on emission abatement cost assessment for electricity generation in the Russian Federation. Other sectors could follow such as oil, non-ferrous metal industries… but also electricity generation and other activities in other countries,
- Actively participate to a joint session of the Coordinating Group for Eastern Europe, the Caucasus and Central Asia and the Expert Group within the Atmosphere-2012 Congress (tentatively scheduled for 16–18 April 2012),
- Translate the relevant documents on techno-economic issues into the Russian language. Presently, the revised guidance document attached to the Gothenburg protocol is being translated.

The work presented hereafter constitutes one of the first pilot studies to be carried out to determine emission reduction costs in the electricity production.
The Apatity combustion plant, located in the Murmansk oblast has been selected for this pilot study.

The Apatity combustion plant produces heat and power and was put in operation in 1959. It is constituted of 10 boilers and 8 steam turbines. Its rated thermal input is 1530 MWth. Coals used have a sulphur content of about 1.5 %. Presently, the plant is equipped with venturi scrubbers to reduce TSP emissions but no other reduction techniques are used.

This study consists in estimating costs of reduction techniques for SO_2, NOx and TSP for this plant, based on information available from EGTEI.

2 CHARACTERISTICS OF THE APATITY PLANT AND EMISSIONS OF POLLUTANTS

2.1 TECHNICAL CHARACTERISTICS

The Apatity plant is constituted of 10 boilers and 8 steam turbines. Each boiler (type PK 10P-2) is a water tube boiler with a rated thermal input of 153 MWth (132 Gcal/h). The total rated thermal input of the plant is 1 530 MWth. Bituminous and sub bituminous coals are used. The characteristics of coals used are as follows:

Table 1: characteristics of coals and liquid fuels consumed in the Apatity plant

Type	Low calorific value	Ash content in operating conditions	Fuel consumption 2008	Fuel consumption 2010
	GJ/t	% w/w	Tons	Tons
Intinskiy (Sub bituminous)	22.80	27.39	225 069	62 350
Vorkutinskiy (Sub bituminous)	22.62	21.37	0	167 386
Kuznetskiy (Bituminous)	17.81	16.77	212 623	171 324
Fuel oil	39.90		655	645
Total			**438 347**	**401 705**

The installation provides electricity and heat. The techno-economic performances are as follows:

- Installed power capacity: 323 MW.
- Installed thermal power: 735 GCal / h (or 852 MWth).

The production of electricity and heat, was as follows in 2008 and 2010:

2008:

- Electricity generation : 419.6 GWh.
- Heat output : 1210.93 $*10^3$ GCal.

2010:

- Electricity generation: 430.2 GWh.
- Heat output: 1279.57$*10^3$ Gcal.

The workload of boilers at the nominal capacity is 1700 hours per year for each of them.

The steam turbines have the following characteristics:

Table 2: characteristics of steam turbines

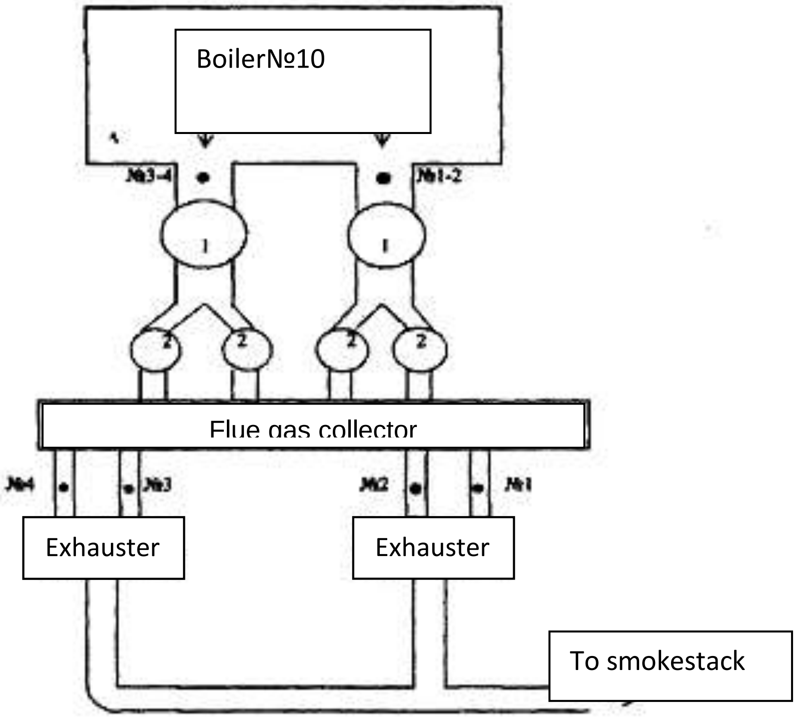
N°	Type of turbine	Characteristics
1, 2	T-36/45/90/2,0	Condensing steam turbine with heating steam extraction
3, 4	PR-28/90/10/2,0	Back pressure steam turbine with process steam extraction
5, 6	R-21/90/8,0	Back pressure steam turbine
7	T-65-90/2,5	Condensing steam turbine with heating steam extraction
8	R-68-90/2,5	Back pressure steam turbine

Boilers are equipped with venturi scrubbers to reduce TSP emissions. The following description has been provided: *"Dust extraction unit consists of two vertical Venturi tubes with throat diameter 1100 mm and length 6,5 m. One Venturi tube tangentially joined to two drip pans with diameter 3100 mm and height of the cylindrical part 8300 mm, height above irrigation belt 6600 mm; irrigation of every drip pan by 30 nozzles with diameter 8 mm. The pressure in drip pan irrigation collectors 0,020 mPa.*

Venturi tubes are irrigated by three centrifugal atomizers EGO with diameter 12 mm and one atomizer with diameter 16 mm. Nozzles are fed directly from water mains with water pressure about 0,35 mPa. Venturi tubes and scrubbers have lined surfaces covered with acid resistant tiles".

The following figure presents the configuration of the flue gas handling after the boiler.

Figure 1: simplified flow sheet of flue gas handling after a boiler PK 10P-2



1 Venturi tube

2 Drip pan

№1 to №4 sampling points after dust and gas treatment system

№1-2 №3-4 sampling points before dust and gas treatment system

Remarks: Monitoring results presented here after, have been done on ducts N°1 to N°4 after the flue gas collector.

There are 3 stacks on the site. Boilers linked to each of them, are as follows:

Table 3: representation of boilers linked to the different stacks

	Rated thermal input of the boiler MWth	Number of hours of work at full load/year hours	Ducts per boiler	Stack
Boiler PK 10P2 n°1	153	1700	1	Stack 1
Boiler PK 10P2 n°2	153	1700	1	
Boiler PK 10P2 n°3	153	1700	1	
Boiler PK 10P2 n°4	153	1700	1	
Boiler PK 10P2 n°5	153	1700	1	Stack 2
Boiler PK 10P2 n°6	153	1700	1	
Boiler PK 10P2 n°7	153	1700	1	Stack 3
Boiler PK 10P2 n°8	153	1700	1	
Boiler PK 10P2 n°9	153	1700	1	
Boiler PK 10P2 n°10	153	1700	1	

2.2 POLLUTANT EMISSIONS OF THE PLANT

Monitoring was conducted in 2010. Concentrations of pollutants monitored are presented here after. Monitoring was carried out on boiler N°5 and boiler N°8.

TSP concentrations were monitored before and after the venturi scrubber. SO_2 and NOx concentrations were also monitored.

During monitoring on boiler N°5, 23.4 t of coal (with a heating value of 22 GJ/t) were consumed. This coal had a sulphur content of 1.16 %. During monitoring on boiler N°8, 25.5 t of coal (with a heating value of 20.6 GJ/t) were consumed. In that case, coal had a sulphur content of 1.43 %.

The results are as follows:

Table 4: concentrations of pollutants monitored on boiler N°5

Boiler PK 10P-2 N°5			
Pollutant	**Monitored concentrations**	**Concentrations**	**Emissions**
	mg/m^3 STP real conditions for O_2	**mg/m^3 STP and 6 % O_2**	**g/s**
Gas duct N°1			
Waste gas flow rate - m^3/s	10.9		
Oxygen % - O_2	9.1	6	
Dust	1795	2263	19.6
NOx	576	726	6.3
SO_2	2 342	2 952	25.5
Gas duct N°2			
Waste gas flow rate - m^3/s	15.8		
Oxygen % - O_2	9.1	6	
Dust	1802	2271	28.5
NOx	576	726	9.1
SO_2	2 342	2 952	37.0
Gas duct N°3			
Waste gas flow rate - m^3/s	20.2		
Oxygen % - O_2	9.8	6	
Dust	2114	2831	42.7
NOx	420	563	8.5
SO_2	2 391	3 202	48.3
Gas duct N°4			
Waste gas flow rate - m^3/s	14.2		
Oxygen % - O_2	9.8	6	
Dust	1783	2388	25.3
NOx	420	563	6.0
SO_2	2 391	3 202	34.0
Average concentrations			
Dust		2 482	
NOx		634	
SO_2		3 093	

Table 4 following: concentrations of pollutants monitored on boiler N°5, summary

Total emissions of boiler N°5 during monitoring	**g/s**	**kg/t coal**	**kg/GJ**	**Efficiency of the wet scrubber**
Dust before venturi scrubber	1 560	240.0	10.91	
Dust after venturi scrubber	116	17.9	0.81	92.6%
NOx	30	4.6	0.21	
SO_2	145	22.3	1.01	

Table 5: concentrations of pollutants monitored on boiler N°8

Boiler PK 10P-2 N°8			
Pollutant	**Monitored concentrations**	**Concentrations**	**Emissions**
	mg/m^3 STP real conditions for O_2	**mg/m^3 STP and 6 % O_2**	**g/s**
Gas duct N°1			
Waste gas flow rate - m^3/s	16.2		
Oxygen % - O_2	8.3	6	
Dust	1 367	1 615	22.1
NOx	812	959	13.2
SO_2	3 689	4 357	59.8
Gas duct N°2			
Waste gas flow rate - m^3/s	14		
Oxygen % - O_2	8.3	6	
Dust	1850	2185	25.9
NOx	812	959	11.4
SO_2	3 689	4 357	51.6
Gas duct N°3			
Waste gas flow rate - m^3/s	15		
Oxygen % - O_2	8.2	6	
Dust	1573	1843	23.6
NOx	851	997	12.8
SO_2	3 032	3 553	45.5
Gas duct N°4			
Waste gas flow rate - m^3/s	13.6		
Oxygen % - O_2	8.2	6	
Dust	1 572	1 842	21.4
NOx	851	997	11.6
SO_2	3 021	3 540	41.1
Average concentrations			
Dust		1 861	
NOx		978	
SO_2		3 963	

Table 5 following: concentrations of pollutants monitored on boiler N°8 summary

Total emissions of boiler N°8 during monitoring	g/s	kg/t coal	kg/GJ	Efficiency of the wet scrubber
Dust before venturi scrubber	1 390	196.24	9.53	
Dust after venturi scrubber	93	13.13	0.64	93.3%
NOx	49	6.92	0.34	
SO_2	198	27.95	1.36	

During monitoring, the sulphur content of fuels used, varied from 1.16 to 1.43 %, with an average of 1.25 % for the two boilers. According to Alexander Romanov [4], the average sulphur concentrations of coals used in the Apatity plant can be estimated to 1.5 %.

On average, emissions of the plant during monitoring, are as follows:

Table 6: average emissions of pollutants during monitoring carried out

Average emissions for the two boilers	kg/t coal	kg/GJ	mg/m^3 STP and 6 % O_2
Dust before venturi scrubber	217.2	10.21	30 455
Dust after venturi scrubber	15.4	0.72	2 158
NOx	5.8	0.27	814
SO_2 (coals with 1.25% S)	25.2	1.19	3 539

The venturi scrubber has an efficiency of about 93%. The air flow rate at 6 % O_2 is about 335 m^3/GJ.

The total emissions of the Apatity plant are as follows, considering a sulphur content of coals of 1.5%:

Table 7: estimated total emissions of the Apatity plant in 2008 and 2010

Total emissions	2008	2010
	tons	tons
Dust before venturi scrubber	91 329	84 593
Dust after venturi scrubber	6 472	5 995
NOx	2 440	2 260
SO_2 based on a sulphur content in coals of 1.5 %	13 096	12 131

In order to estimate costs of reduction techniques, an average situation between 2008 and 2010 has been taken into account for the consumption of fuels. Sulphur concentrations are a little bit larger than in table 6 due to the sulphur content larger (1.5 % instead of 1.25 %). Emissions are estimated to:

Table 8: average emissions of pollutants used for cost estimation

Average emissions for the two boilers	kg/t coal + heavy fuel	kg/GJ	mg/m^3 STP and 6 % O_2
Dust before venturi scrubber	209.4	10.21	30455
Dust after venturi scrubber	14.8	0.724	2158
NOx	5.6	0.273	814
SO_2	30.0	1.464	4367

The average consumption of fuels and total emissions taken into account to estimate costs, are as follows:

Table 9: average consumptions of coals and heavy fuel oils and emissions taken into account for the cost assessment

	Average situation for cost determination
Consumption of coals (1.5 % S)	419 376 t or 8 588 760 GJ
Consumption of heavy fuel oils (2.48 %)	650 t or 25 935 GJ
Dust before venturi scrubber	87 961
Dust after venturi scrubber	6 234
NOx	2 350
SO_2 based on the sulphur content in coals of 1.5 %	12 614

3 COMPARISON OF EMISSIONS OF THE APATITY PLANT WITH ELV PROPOSED IN ANNEX IV FOR SO_2, ANNEX V FOR NOx AND ANNEX X FOR DUST

Average concentrations of pollutants of the Apatity plant can be compared to options presented in the draft technical annex IV for SO_2, the draft technical annex V for NOx and the draft technical annex X for dust [2]. The comparison is as follows:

Table 10: comparison of average pollutant concentrations monitored on the Apatity plant with options for negotiations of technical annexes IV, V and X [2]

	Average concentration of boilers N°5 and N°8	**Option 1**	**Option 2**	**Option 3**
	mg/m³ STP and 6 % O_2			
Dust before venturi scrubber	30 455	10	20	50
Dust after venturi scrubber	2 158	10	20	50
NOx	814	100	200	200
SO_2	4 367	100	200	1 200

Option 2 corresponds to the upper level of Best Available Techniques Associated Emission Levels used for reducing SO_2, NOx and dust in LCP [10].

For SO_2, the required efficiency is at least of 95.4%. The ELV cannot be reached by the use of low sulphur coals. These coals do not exist. Wet Flue Gas Desulphurisation (FGD) using lime or limestone as reagent, can be used to achieve this level of abatement.

For NOx, the required efficiency is at least of 75.4%. The abatement level can be achieved with a Selective Catalytic Reduction (SCR) technique.

For dust, the required efficiency is at least of 99.93 % taking into account the abandon of the venturi scrubbers. Such an efficiency and emission level can be obtained by an electrostatic precipitator (ESP).

4 ESTIMATION OF COSTS OF REDUCTION TECHNIQUES

4.1 EQUIPEMENT REQUIRED AND ASSUMPTIONS

To reduce pollutant emissions up to the levels required by option 2 proposed in the technical annexes associated to the Gothenburg protocol in revision, techniques such as the wet flue gas desulphurisation (FGD) for SO_2, the selective catalytic reduction (SCR) for NOx and the Electrostatic Precipitator (ESP) for dust can be used. EGTEI has developed cost estimation for those techniques which are applied for the Apatity plant, considering the characteristics of the plant.

In **wet FGD**, SO_2 is removed by scrubbing the flue gas with either a limestone or lime slurry. The following reaction is involved with limestone:

$SO_2 + CaCO_3 + ½\ H_2O \rightarrow CaSO_3.\ ½H_2O + CO_2$

Two different modes to treat the by products exist. In the natural oxidation mode, calcium sulphite is partly oxidised by the oxygen contained in the flue gas. The slurry obtained has no recovery application and must be disposed according to local rules, after specific treatment such as dewatering. In the process with forced oxidation, air is bubbled through the slurry of the calcium sulphite hemi hydrate obtained to form gypsum which is saleable for plaster production as example, according to the following reaction:

$CaCO_3.½\ H_2O + ½\ O_2 + 1.5\ H_2O \rightarrow CaSO_4.2H_2O$

Wet FGD is widely used for coal power plants around the world.

In the case of this study, wet FGD with forced oxidation is proposed to be used. In natural oxidation system indeed, by products obtained are wastes which must be disposed. On contrary, in the forced oxidation mode, saleable products are obtained. This reduces overall costs.

A wet FGD system operates at low temperatures between 45 and 60 °C and is the most often located at the end of the chain of reduction equipment.

The **SCR process** is a catalytic process based on the selective reduction of nitrogen oxides with ammonia (or urea) in the presence of a catalyst. The reducing agent is injected into the flue-gas upstream of the catalyst. NOx conversion takes place on the catalyst surface at a temperature usually between 300 to 450 °C. Ammonia is used in a liquefied form or in aqueous solution. Catalysts based on metal oxides need temperature between 300 and 450 °C to be operational. The catalyst lifetime ranges from 40 000 to 80 000 hours.

Several arrangements of the chain of equipment are possible but in order to avoid air reheating if the SCR unit is placed at the end of the chain, the SCR is placed in first position, just after the boiler. This high dust configuration has some drawbacks: the catalyst can be deactivated by fly ashes and possible poisons. Space is needed around the boiler. The SCR unit can be placed just after an electrofilter placed in first position. In this low dust configuration, dust is removed in a high temperature electrofilter. The catalyst lifetime can be extended [10].

With SCR, ammonia split can be obtained. The concentrations depend on the ratio NH^3/NOx and can be maintained to less than 5 mg/m^3 (STP) by a correct dimensioning of the SCR unit and a good mix of NH_3 and NOx.

Electrostatic precipitators (ESP) are commonly used to reduce TSP emissions from coal combustion plants. The TSP removal efficiency can be very high but requires good maintenance programme. The efficiency depends on the surface area of electrodes, the speed of waste gas and the migration velocity of particles. A 3 to 4 field ESP enables to reach 20 mg/m^3 (STP) of TSP if it has been well dimensioned.

In the Apatity plant, flue gases are presently treated to remove TSP by venturi scrubbers. The efficiency of these scrubbers is about 93 %. TSP concentrations are about 2.1 g/m^3 (STP). After the venturi scrubber, the temperature is about 70 °C.

In the proposal done in this study, the scrubbers are not kept in operation. Indeed, the temperature required by a SCR is between 300 °C and 400 °C. This temperature would require reheating of flue gases which is not economical and reduce the efficiency of the plant, if the venturi scrubbers are maintained in operation.

The following chain and configuration is proposed:

A SCR unit is placed at the outlet of each boiler in a high dust configuration. The temperatures are assumed to be sufficient to avoid reheating. An ESP is located just after the SCR unit. Each boiler is equipped in the same way.

A common FGD unit is installed, after the collection of flue gases coming from the 10 boilers.

The EGTEI methodology for cost estimation of reduction techniques for LCP [3] provides estimation of costs for those techniques.

The prices of utilities, wages, and reagents taken into account are as follows :

Electricity: 0.1 €/kWh [4]

Wages: 6 k€/person/year [4]

Waste disposal: 8.3 €/t [4]

Lime stone: 20 €/t $CaCO_3$. Cost assumed to be similar to costs in the EU.

NH_3: 400 €/t NH_3. Cost assumed to be similar to costs in the EU.

Investments available in the literature are mainly expressed in € or $/kWe without providing the electrical efficiency. Investments are provided for existing plants. An average electrical efficiency of 39 % is assumed according to information provided by an expert [11], except if the information is provided.

4.2 WET FGD

The capital costs of the FGD depend on [5]:

- volume of gases to be treated,
- concentrations of SO_2 in flue gases,
- desulphurisation efficiency required,
- quality of by products produced,
- other environmental constraints…

Investments :

For an efficiency of 95 %, the current EGTEI methodology gives an investment cost which ranges from 90 M$€_{2000}$ or 58.8 $€_{2000}$/MWth to 109 M$€_{2000}$ or 71.5 $€_{2000}$/MWth. The IEA clean coal center [5] provides control costs for wet FGD with forced oxidation which are on average of 200 $€_{2000}$/kWe. Taking into account an average overall efficiency of 39%, the average cost is 78.1 $€_{2000}$/kWth. Reference [6] provides average costs which are about 38.8 $€_{2007}$/MWth. Reference [7] provides costs ranging from 73.4 to 80.8 $€_{2000}$/kWe or 28.6 to 31.5 $€_{2000}$/kWth

Considering the cost index from 2000 to 2007 of 1.33, EGTEI cost data seem a little bit too high compared to reference [6] and [7] but a little bit too low compared to reference [5]. The reference [6] providing some recent data, is taken in reference.

Considering the cost index between 2007 and 2010 of 1.07, the investment cost is assumed to be 63.56 $€_{2010}$/MWth.

Operating costs:

Operating cost functions from EGTEI are applied:

<u>Electricity cost</u>:

$C^{elect} = \lambda^{e} * c^{e} * 10^{3}$ [k€/PJ fuel input/y]

λ^{e} : electricity demand [GWh/PJ fuel input]

c^{e} : electricity price [€/kWh]

The electricity demand is 2.36 GWh/PJ for wet FGD with an efficiency of 95 %.

For Apatity:

The annual electricity costs can be estimated to: 236.6 k€/PJ or 2 033 k€/year.

<u>$CaCO_3$ cost:</u>

$C^{CaCO3} = \lambda^{s} * c^{s} * ef_{unabated} * \eta / 10^{3}$ [k€/PJ fuel input/y]

$ef_{unabated}$: unabated emission factor of pollutant [t SO_2/PJ fuel input]

λ^{s} : specific limestone demand [ton $CaCO_3$/ton SO_2 removed]

c^{s} : $CaCO_3$ price [€/ton $CaCO_3$]

η : removal efficiency $((ef_{unabated} - ef_{abated})/ef_{unabated})$

For Apatity:

For an efficiency required of about 95 %, the ratio Ca/S is about 1.02. The demand in $CaCO_3$ is consequently of 1.59 ton/ton of SO_2.

The annual $CaCO_3$ costs can be estimated to: 44.4 k€/PJ or 382.7 k€/year.

Labour cost:

$\underline{C}^{lab} = (\lambda^{l} * c^{l}) * 10^{6} / (3.6 * pf)$

[k€/PJ fuel input/y] [man-year/MWth]

$\underline{C}^{lab} = (\lambda^{l} * c^{l}) * 10^{3} / (3.6 * pf)$ [k€/PJ fuel input/y]

[k€/PJ fuel input/y] [man-year/GWth]

λ^{l} : labour demand [person-year/MWth] or [person-year/GWth]

c^{l} : labour cost/wages [€/person-year]

pf : annual operating hours at full load [h/y]

The labour demand taken into account is 6.5 persons-year/GWth for wet FGD with an efficiency of 95 %.

For Apatity:

The annual labour costs can be estimated to: 6.4 k€/PJ or 55.21 k€/year.

Waste disposal cost:

Gypsum is produced. There is not waste disposal cost. It is assumed no revenue from the sale of gypsum.

Total costs – summary:

Total annual costs can be summarised as follows:

Investment	$k€_{2010}$/year	63 560
Annualised capital costs	$k€_{2010}$/year	5 720
Fixed operating costs	$k€_{2010}$/year	2 540
Electricity costs	$k€_{2010}$/year	2 030
Reagent costs	$k€_{2010}$/year	383
Labour costs	$k€_{2010}$/year	55
Total operating costs	$k€_{2010}$/year	5 010
Total annual costs	$k€_{2010}$/year	10 730

The FGD enables to reduce the emissions of SO_2 from 12.6 kt to 0.58 kt or 12.0 kt of SO_2 eliminated.

The average costs are 892 €/t SO_2 abated.

4.3 ESP

Investments:

To obtain a concentration of 20 mg TSP/m^3 (STP), the current EGTEI methodology gives an investment of about 17.3 $M€_{2000}$ or 11.3 $€_{2000}$/MWth for a plant of 1530 MWth. Reference [8] provides average costs coming from the reference 7. Costs are provided in Euro 2008 and vary from 11.5 to 12.7 $€_{2008}$/MWth. Compared to EGTEI data, investments seem to be a little bit larger. A factor of 1.07 is obtained.

EGTEI investment function has been modified to better reflect recent data and cost for 2010 have been derived from costs for 2008 using the chemical engineering cost index. Costs for the boiler of 153 MWth have been derived using the scale exponent method [9].
The investment for the Apatity plant can be estimated to 30.7 $M€_{2010}$.

Operating costs:

<u>Electricity cost</u> :

$C^{elect} = \lambda^e * c^e * 10^3$ [k€/PJ fuel input/y]

λ^e : electricity demand [GWh/PJ fuel input]

c^e : electricity price [€/kWh]

The electricity demand is 0.2 GWh/PJ for an ESP achieving 20 mg/m^3 (STP).

For Apatity:

The annual electricity costs can be estimated to: 20 k€/PJ or 172.3 k€/year.

<u>Labour cost:</u>

$\underline{C}^{lab} = (\lambda^l * c^l) * 10^6 / (3.6 * pf)$

[k€/PJ fuel input/y] [man-year/MWth]

$\underline{C}^{lab} = (\lambda^l * c^l) * 10^3 / (3.6 * pf)$ [k€/PJ fuel input/y]

[k€/PJ fuel input/y] [man-year/GWth]

λ^l : labour demand [person-year/MWth] or [person-year/GWth]

c^l : labour cost/wages [€/person-year]

pf : annual operating hours at full load [h/y]

The labour demand taken into account is 2 persons-year/GWth.

For Apatity:

The annual labour costs can be estimated to: 1.96 k€/PJ or 16.9 k€/year.

<u>Waste disposal cost:</u>

$C^{was} = \lambda^d * c^d * ef_{unabated} * \eta / 10^3$ [k€/PJ fuel input/y]

$ef_{unabated}$: unabated emission factor of pollutant [t pollutant/PJ fuel input]

λ^d : demand for waste disposal [ton/t pollutant removed]

c^d : byproduct/waste disposal cost [€/ton]

η : removal efficiency (= $1 - ef_{abated}/ef_{unabated}$)

There is 1 ton of waste per ton of TSP removed.

For Apatity:

The annual waste disposal costs can be estimated to: 84.7 k€/PJ or 729.6 k€/year.

Total costs – summary:

Total annual costs can be summarised as follows:

Investment	k€$_{2010}$	30 734
Annualised capital costs	k€$_{2010}$/year	2 764
Fixed operating costs	k€$_{2010}$/year	1 229
Electricity costs	k€$_{2010}$/year	172
Waste disposal costs	k€$_{2010}$/year	730
Labour costs	k€$_{2010}$/year	17
Total operating costs	k€$_{2010}$/year	2 148
Total annual costs	k€$_{2010}$/year	4 912

The ESP enables to reduce the emission of TSP from 87 960 t to 58 t or 87 900 t of TSP eliminated.

The average costs are 56 €/t TSP abated.

4.4 SCR

Investments for a SCR depend on the following parameters [5]:

- catalyst and reactor system,
- flow control and valving system,
- ammonia injection grid,
- ammonia storage,
- all piping,
- flues, expansion joints and dampers,
- fan upgrades,
- foundations,
- structural steel and electricals,
- installation.

For this estimation a catalyst lifetime of 56000 hours has been taken into account.

Investments:

Costs provided by the current EGTEI investment cost function have been compared to relevant data of the literature. For a SCR with an efficiency of about 75 % for a plant of 1530 MW, the current EGTEI methodology with updated costs for catalysts, gives an investment of about 35.7 M€$_{2000}$ or 23.4 €$_{2000}$/MWth. Reference [8] provides average costs coming from different sources which are mainly from 2000. Costs are on average of 49.2 €/kWe or 19.2 €/kWth. According to reference [6], the average costs for a SCR is about 136 £$_{2007}$/kWe or 93 €$_{2007}$/kWe.

Reference [5] provides data according to the size of the plant and the inlet NOx concentrations. For large installations above 400 MWe and concentrations above 738 mg/M3 (STP), the average cost is 53 \$$_{2000}$/kWe. This gives 43.7 €$_{2000}$/kWe or 19.2 €$_{2000}$/kWth. At lower size, between 50 and 200 MWe, the costs are 75 €$_{2000}$/kWe or 29.3 €$_{2000}$/kWth.

The EGTEI cost function has been adapted to better reflect the data from the literature for 2000. The cost function has also been adapted to provide investment in € 2010 by using the chemical engineering cost index of 1.41 from 2000 to 2010.

Investments for a boiler of 153 MWth are derived using data from reference [5] which provides the ratio between a large boiler and a smaller one presented above.

The investment for the 10 boilers of the Apatity plant can be estimated to 62.8 M€$_{2010}$.

Operating costs:

<u>Electricity cost</u>:

$C^{elect} = \lambda^e * c^e * 10^3$ [k€/PJ fuel input/y]

λ^e : electricity demand [GWh/PJ fuel input]

c^e : electricity price [€/kWh]

The electricity demand for a SCR on a coal boiler is 0.36 GWh/PJ according to EGTEI.

For Apatity:

The annual electricity costs can be estimated to: 36 k€/PJ or 310.1 k€/year.

Labour cost:

$\underline{C^{lab}} = (\lambda^{l} * c^{l}) * 10^{6} / (3.6 * pf)$

[k€/PJ fuel input/y] [man-year/MWth]

$\underline{C^{lab}} = (\lambda^{l} * c^{l}) * 10^{3} / (3.6 * pf)$ [k€/PJ fuel input/y]

[k€/PJ fuel input/y] [man-year/GWth]

λ^{l} : labour demand [person-year/MWth] or [person-year/GWth]

c^{l} : labour cost/wages [€/person-year]

pf : annual operating hours at full load [h/y]

The labour demand is 1.2 person-year per GWth.

For Apatity:

The annual labour costs can be estimated to: 1.17 k€/PJ or 10.1 k€/year.

Catalyst cost

$\underline{C^{cat}} = (\lambda^{cat} * ci^{cat} / lt^{cat}) * (10^{3} / 3.6)$ [k€/PJ fuel input/Year]

λ^{cat} : catalyst volume (per unit of installed capacity) [m^3/MWth]

ci^{cat} : unit costs of catalysts [k€/m^3]

lt^{cat} : life time of catalyst [10^3 hrs]

The catalyst demand is 0.5 m^3/MWth.

The catalyst cost is about 20 k€/m^3.

The lifetime of the catalyst is 56 000 hours.

For Apatity:

The annual catalyst costs can be estimated to: 49.6 k€/PJ or 427.3 k€/year.

$\underline{NH_3}$ cost :

$C^{NH}{}_{3} = \lambda^{s} * c^{s} * ef_{unabated} * \eta / 10^{3}$ [k€/PJ fuel input/a]

$ef_{unabated}$: unabated emission factor of pollutant [t NOx/PJ fuel input]

λ^{s} : specific limestone demand [ton NH_3/ton NOx removed]

c^{s} : NH_3 price [€/ton NH_3]

η : removal efficiency $((ef_{unabated} - ef_{abated})/ef_{unabated})$

For Apatity:

For an efficiency required of about 75 %, the demand in NH_3 is of 0.34 ton NH_3/ton NOx.

The annual NH_3 costs can be estimated to: 27.85 k€/PJ or 239.9 k€/year.

Total costs – summary:

Total annual costs can be summarised as follows:

Investment	k€$_{2010}$	62 870
Annualised capital costs	k€$_{2010}$/year	6 830
Fixed operating costs	k€$_{2010}$/year	1 900
Electricity costs	k€$_{2010}$/year	310
NH3 costs	k€$_{2010}$/year	240
Labour costs	k€$_{2010}$/year	10
Catalyst replacement	k€$_{2010}$/year	427
Total operating costs	k€$_{2010}$/year	2 890
Total annual costs	k€$_{2010}$/year	9 718

The SCR enables to reduce the emission of NOx from 2 352 t to 588 t or 1 764 t of NOx eliminated. The average costs are 5 509 €/t NOx abated.

5 SYNTHESIS OF RESULTS OBTAINED

The following table presents of summary of costs estimated to reduce emissions of SO_2, TSP and NOx from the Apatitity combustion plant.

	SO_2	**NOx**	**TSP**
Investments - k€ $_{2010}$	63 559	62 868	30 734
Operating cost - k€ $_{2010}$ / year	5 013	2 890	2 148
Total annual costs - k€ $_{2010}$/year	10 730	9 718	4 912
Initial annual average emissions - tons	12 612	2 352	87 961
Emissions abated - tons	12 034	1 764	87 903
Pollutants emitted - tons	578	588	58
Cost € $_{2010}$/t pollutant abated	892	5 509	56

The implementation of the 3 reduction techniques beginning by a couple SCR and ESP at the outlet of each boiler (10 couples in total) and then, a wet FGD treating waste gases collected from the 10 boilers, has probably a minimum cost of 157.2 M€$_{2010}$. The annual total costs are about 25.4 M€$_{2010}$/year. On average the electricity consumption represents 5.9 % of the electricity produced by the plant.

These costs are probably underestimated as, with the EGTEI methodology, average costs of reduction techniques are only estimated. The degree of the complexity of the retrofit is not known in the scope of this study. Average retrofit factors have been used. Investments can increase with the degree of the difficulty. One factor which cannot be appreciated is, for example, the availability of place on the site after each boiler to install a SCR unit and an ESP. The configuration adopted requires a huge change in the flue gas handling. Venturi scrubbers are no more used nor the existing chimneys. All these changes require adaptations of command controls of boilers and pressure equipment.

The study carried out cannot replace a detailed site specific engineering cost study but provides useful information for the assessment of the economical impact of regulation.

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