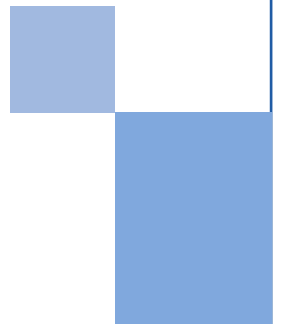**RWE Power International**

Engineering Report

Technical and Economic Analysis of Supercritical PF Plant Suitable for Greek Lignite

Reference Number: **P0749-RAE Greece**
Date: April 2006
Issue: Final

Presentation
Egbert Reinartz

Technical and Economic Analysis of Supercritical PF Plant Suitable for Greek Lignite

Prepared for:

Client Contact :	
Contract No. :	

Prepared by: Egbert Reinartz Ulrich Mohn Dr. Bernd Heiting Dr Phil Cahill	

Reviewed by:	Authorised by: Dorian Matts, Manager, Boilers and Combustion Team

Executive Summary

In this report RWE Power International presents an objective assessment of the current status of technology, and an outlook for further development of this technology over the next decade. The impact of Greek lignite's (Florina, Ptolemais and Drama) were evaluated, and imported hard coal from South Africa (Forzandu) and Russia (Taldinskaya, Kuzbas) were compared for all potential clean coal technologies. The issues associated with installing flue gas desulphurisation plants (FGD) for lignite and coal are compared. The FGD technology is described in detail, based on experience from Germany.

		Drama	Ptolemais	Florina	Rhenish	Forzando	Taldins -kaya
Total	%	57.8	51.1	37.4	53.0	9.2	10.6
Moisture							
Ash	%	16.1	17.3	27.2	5.0	13.0	8.9
LHV (ave)	MJ/kg	4.38	5.37	7.89	8.70	24.82	25.33

The ash composition and ash properties of the Greek lignite's are also significantly different, with higher propensity to deposition.

In terms of boiler technology the lignite's may be ranked as follows:
1) Rhenish lignite: High LHV, high moisture content, small ash content
2) Florina lignite: High LHV (comparable to Rhenish lignite), low moisture content, high ash content
3) Ptolemais lignite: Low LHV, high moisture content, high ash content
4) Drama lignite: Lowest LHV, high moisture content, high ash content

The combination of high moisture and high ash content (hence low LHV) for the Drama and Ptolemais lignite's creates a combustion problem and this would need to be quantified before design of a new boiler.

This information will assist RAE in Greece in the development of a strategy for coal fired power generation in Greece.

Technology Assessment: Power Generation Technologies (PFC, CFB, IGCC)

For lignite's, the most developed technology is supercritical PF combustion. State of the art plant has been built and operated at commercial scale and high efficiency is possible although this is lower than for bituminous coal due to increased flue gas losses for lignite's. The application of pre-drying of lignite's overcomes efficiency losses due to the high moisture.

FBC technology has a role for smaller (<250MW) lignite plant due to lower capital cost. However, at this scale plant will be at a lower steam conditions than supercritical PF and hence will be less efficient.

PFBC and IGCC technologies are still relatively unproven and the demonstration plants vary significantly in design. In both cases, pre-drying of the lignite is required for optimum efficiency and in the case of IGCC the use of pre-drying may lead to efficiencies as high as for the supercritical PF plant.

In PFBC, the efficiency is likely to be lower than for IGCC and supercritical PF due to the lack of hot gas cleaning. Fluidised bed gasifiers are suited to lignite gasification

although pre-drying may widen the ability to use other gasification technologies. Due to the ash characteristics of Greek lignite's, use of entrained flow gasifiers would be unsuitable. This may also present problems in PFBC application through deposition in the cyclones, hot gas filters as well as a propensity for bed agglomeration.

Emission Reduction Technologies (NO$_X$ and SO$_X$)

NO$_X$ Reduction:

The NO$_X$ produced from a PF fired combustor can be reduced by primary (combustion zone) and secondary measures (post combustion). Primary NO$_X$ reduction can be achieved through air staging, modifications to the burners, secondary air system, additional flue gas re-circulation system and reducing excess air for combustion. Air staging has been installed in lignite fired power plant and has been demonstrated to successfully meet the requirement of the regulations.

Secondary NO$_X$ reduction measures involve ammonia injection and the use of catalysts and have been fitted successfully upstream or downstream of the airheaters and electro static precipitators.

SO$_2$ Reduction:

The Florina, Ptolemais and Drama sites have no great process differences to the FGDs implemented in the Rhenish lignite region. To achieve an economic absorber size for the Greek lignite powered stations, the specified coal sulphur content for each of the three Greek lignite sources should be confirmed to avoid over-sizing the FGD. This applies especially to the Drama lignite site.

FGD in power stations fired with the imported coals also show no great process differences for the Russian and South African coals. These coals have very low sulphur content. It is, however, advisable to design the FGD for these applications for a higher sulphur content to enable a wider range of world market coals to be used in the future.

Technologies for CO$_2$ Reduction:

BoA Technology:

As no industrial-scale and commercial solutions are yet available for CO$_2$ reduction (e.g. like filters, separators and similar), reductions can only be achieved by increase of efficiency. With an efficiency of more than 43% compared with 31% for old units, the BoA technology unit meets this goal.

The BoA Technology applies the most advanced technological developments across all components and systems of the power station to maximise efficiency. This includes application of new materials for the tubes in the high temperature area of the boiler to enable an increase in the process parameters and hence efficiency. Using these improvements, a net efficiency of 43% can be achieved from a lignite unit. To achieve specific cost optimisation, the BoA unit is designed for a gross output of 1100 MW.

The table below indicates the net unit efficiencies that should be attainable for the application of BoA in the context of Greek lignite firing. The differences of the coal quality between Rhenish and Greek result in a reduction in boiler efficiency reduction due to higher flue gas mass-flow (flue gas losses) and the higher ash content (losses of unburnt coal).

	Units	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Turbine Heat Consumption	%	49.0	48.0	48.0	48.0
Boiler efficiency	%	93.0	87.0	88.6	89.7
Auxiliary Power Consumption	%	5.0	6.0	6.0	6.0
Unit Net Efficiency	%	43.3	39.3	40.0	40.5

An analysis of the required investment for a BoA plant for Greek lignite (Drama and Ptolemäis) was performed and is presented in the table below. The main impact of coal quality concerns the boiler and flue gas plant with FGD and Precipitator, resulting in a 7% increase in specific capital cost. The capital required was also calculated for a reduced-scale 600MWe case.

		Rhenish lignite	Greek lignite
Specific Capital – 1100 MWe	€/kW	1100	1177
Specific Capital – 600 MWe	€/kW	1359	1455

As an additional efficiency improvement, RWE Rheinbraun has developed a new "fluidised-bed" drying process WTA. Using fine milling and WTA techniques, the 1,050 MWnet BoA-Plus power plant was developed with a unit net efficiency of 47%. Firing of pre-dried lignite has a significant impact on the design of the boiler and therefore cannot be retrofitted economically.

Gas Turbine Repowering:

A further possibility for CO_2 decrease may be achieved through integration of a gas turbine firing natural gas with lignite fired plant:

- CO_2 emissions are reduced as carbon is replaced by hydrogen from the natural gas.
- The efficiency of the plant is increased by connecting the gas turbine to the lignite unit; heating the lignite unit condensate after the condenser using the waste heat from the gas turbine.

From economic view the employment of the gas turbine depends on the natural gas price and attainable price for peak load operation.

Table of Contents

1.   Introduction

The Regulatory Authority for Energy (RAE) of the Hellenic Republic has requested RWE Power International to conduct a 'Clean Coal Technologies Overview'.

This report is submitted in fulfilment of the requirements of task 3 and comprises the assembly and evaluation of information that will assist RAE in the development of a strategy for coal fired power generation in Greece.

The report describes the formation of NOx in the combustion process, measures to reduce NOx for lignite and hard coal firing systems.

In preparing this report RWE Power International has relied on its extensive experience and knowledge of power technology. Power plant owners, operating in commercial competitive markets do not release useful information on the reliability of their power plants or on their maintenance requirements. In this report RWE Power International presents an objective assessment of the current status of technology, and an outlook for further development of this technology over the next decade; limited economic facts are also discussed.

This report consists of eight chapters. In each chapter a brief description of the technology, its environmental performance, demonstrated commercial performance, efficiency, technology status and its future potential refers to the Greek coal characteristics.

Also described in the report are the issues for retrofitting existing plants. Also for new plants the state of the art technology and the development for the next decade are described including the impact on Greek lignite. To reduce SOx emission the process of flue gas desulphurisation (FGD) is required and the development of the technology in Germany, the difference in FGD technology in lignite and hard coal power stations is described. The influence of the Greek lignites and of the imported coals on the FGD process is shown.

In further chapters the economic aspects and a conclusion is given. References to the described technology and methodology for further detail is given.

It must be noted that site specific and project O&M, plant running and personnel cost, availability factors and forced outage rates could not be determined. This information is considered sensitive and for commercial and confidentiality reasons is not available as public domain information.

2.   Fuel and Technology Assessment

2.1. Greek Lignite

Greek lignite has high moisture and ash contents. This results in a low calorific value of the coal and requires additional throughput from the firing systems to achieve the same plant output. In the following diagram, Greek lignite is compared with lignite from other sources.
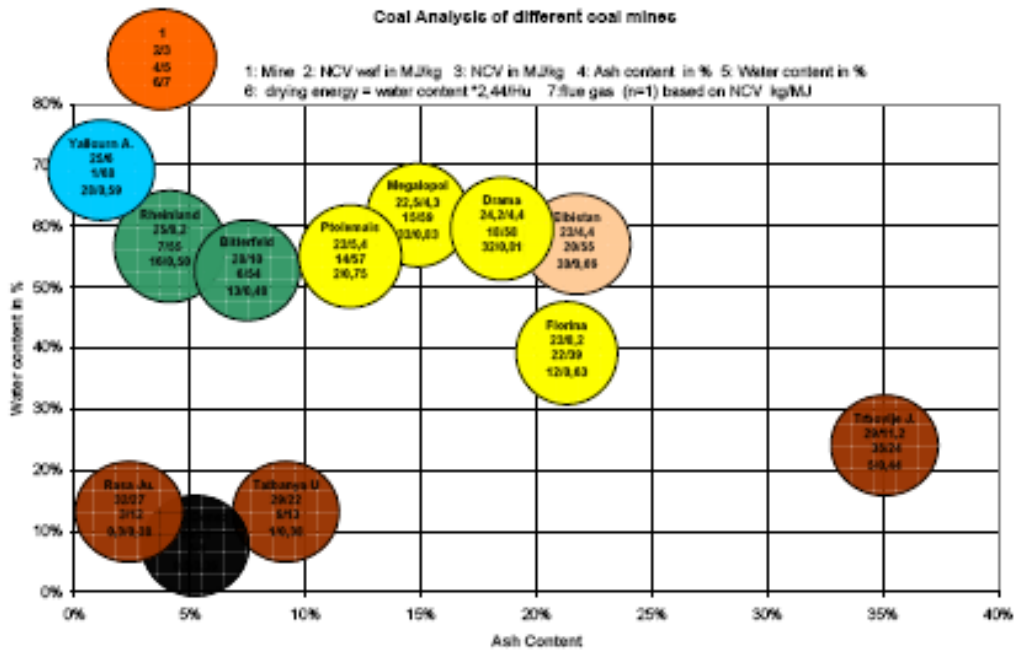
Figure 1: Engineering and Economic Assessment of Various Technologies with Domestic Lignite and Imported Bituminous Coal

The three lignite fuels Drama, Florina and Ptolemais were considered together with Taldinskaya and Forzando coals for the technologies considered in Task (Ref 15).

- Conventional Supercritical PF Combustion
- Fluidised Bed Combustion
- Integrated Gasification Combined Cycle
- Power Plants with CO2 Carbon Capture

For each technology the impact of the fuel type was considered for capital and operating cost, potential plant issues, environmental impacts and plant efficiency.

There are significant differences between the types of coal considered in this project. The lignites have very low net heat contents (NCV) and very high total moisture contents compared to the two internationally-traded bituminous coals. This means that for a given plant the tonnage of lignite required to be handled, milled and burned is significantly higher than for bituminous coals. The key properties are summarised in Table 3.1 below. The sulphur content for the Florina coal from the Geological survey data was 0.7%, although the more normal range is 0.4-2.7% with an average of 1.1%. Similarly, the Geological survey data for the Drama coal appeared to be too low at 0.1%, whereas the analysis data suggested 1.63%. A range was used for the Drama sulphur content to show the impact of sulphur content.

2.1.1. Coal Properties

		Drama	Ptolemais	Florina	Forzando	Taldinskaya RWE database spec
Total Moisture	%	57,8	51,1	37,4	9,2	10,6
Inh. Moisture	%				3,6	4,6
Ash	%	16,1	17,3	27,2	13,0	8,9
VM	%		17,2	21,8	25,1	32,1
CO2	%		3,3	0,4		
FC	%		11,2	13,7	52,7	48,4
Fuel Ratio			0,65	0,63	2,1	1,51
LHV (average)	MJ/kg	4,380	5,368	7,89	24,82	25,33
Carbon		16,1	18,7	27,1	65,2	64,9
Hydrogen		1,40	1,60	2,2	3,79	4,36
Nitrogen		0,40	0,20	0,2	1,63	1,93
Sulphur	%	0,1-1,63	0,40	0,7	0,76	0,30
HGI					50	50
IDT$_{red}$	deg C				1350	1298
HT$_{red}$	deg C				1380	1390
FT$_{red}$	deg C				1400	1437
SiO2	%	19,6-55,4	9,1-55,3	26-48,2	49,1	69,2
Al2O3	%	6,8-24,3	8,1-24,3	12,5-26,1	29,5	17,9
Fe2O3	%	2,5-13,0	5,3-10,1	10-11,1	3,5	3,3
TiO2	%	0,2-0,9	0,4-1,1	0,6-1,1	1,4	0,7
P2O3	%	<0,3	<0,6	0,3-0,6	0,5	0,8
CaO	%	7,4-63,4	20,1-56,4	6,9-30,0	9,4	4,3
MgO	%	2,2-4,1	2,2-8,8	2,8-3,2	2,1	1,9
Na2O	%	0,6-1,3	<0,7	<0,1	0,36	0,7
K2O	%	0,8-1,0	0,8-1,9	0,3-0,6	0,46	0,4
SO3	%	13,5-32,7	0,8-21,4	2,9-12,9	2,03	1,0

A key difference between the types of coal is the ash composition and ash properties. Internationally traded hard coals such the Russian and South African coals in the table above have high ash fusion temperatures and relatively low sodium content. The lignites have significant range in properties but are generally high in calcium compared to bituminous coals.

2.2. Supercritical PF Combustion

Modern supercritical boilers can have boiler efficiencies up to 96% (LHV) but more commonly have values of up to 94-95% (LHV) when burning hard coals. The boiler efficiency for lignites is generally several points lower than this and is typically 90-91% (LHV). The key reason for the difference is the increase in loss of heat in the flue gases due to the additional volume of gas and the requirement to operate with a higher boiler flue gas temperature due to the higher dew point of the sulphuric acid. The value of this dew point depends on the water content of the flue gas, which is much higher in the lignite than in the hard coal. For a given load on a boiler, the flue gas flow for the Greek lignites was predicted to be up to 50% higher than for the two hard coals, this is due mainly to the additional moisture in the fuel and the higher flue gas temperatures. The Drama lignite was predicted to give highest flue gas loss due to it having highest moisture and this could be up to 4% higher than for the hard coals. Estimates of losses due to unburned carbon give the highest loss for the South African coal and lowest for the Taldinsky. However, the difference between the highest and lowest values is 1% of LHV. The actual values would depend on the plant designs, e.g. milling plant type, burner and boiler design.

A key issue for supercritical boiler design is the Furnace Exit Gas Temperature (FEGT). In order to avoid severe deposition in the convective heat transfer part of

11

the boiler it is necessary to ensure ash particles are not still molten at this point. Typically, the design FEGT is at least 50°C lower than the lowest value expected for the IDT for the coal range under consideration. Typical values for FEGT for stations burning hard coals are in the range 1150-1200°C. For lignite burning plants, the FEGT is typically 150- 200°C less than this. The Greek lignites in Table 3.1 can be seen to have considerable variability in ash composition and in particular iron and calcium contents have significant impact on IDT_{red} values. The net result is that lignite boilers need to be taller and have a much greater cross section than boilers for hard coals, thus resulting in significantly higher capital cost. Increased soot blowing is also required for these boilers to control FEGT and NOx emissions.

The size of the coal and ash handling plants are much increased when burning the lignites, for instance.

- The relative fuel burn rates required for the Florina, Ptolemais and Drama lignites are estimated to be 3.3, 4.8 and 5.9 times higher, respectively, than for the hard coals which are similar.
- Estimated ash production for the Florina, Ptolemais and Drama lignites are estimated to be 6.7, 7.1 and 7.7 times higher, respectively, than for the hard coals which are similar.

The milling plant for the lignites is fundamentally different to the mills for the hard coals. The key issue for lignites is to achieve adequate drying and to avoid mill fires. This is achieved using flue gas in addition to air for drying and this gives the heat required and also reduces the oxygen concentration in the mills to a level where explosion cannot occur. The hard coals do not require such measures as they can be milled safely without flue gas. Air heaters alone provide adequate temperature of air for drying (about 200 °C). The types of mills are fundamentally different with beater mills for lignite and vertical spindle or tube ball mills for hard coals. Particle size must be smaller for the hard coals than for the lignites because the hard coals are less reactive and for a given particle size they take longer in the boiler to achieve adequate burn-out. Achieving lower particle size in the mills helps to achieve adequate burn-out in shorter times.

Many modern hard coal mills require dynamic classifiers to achieve the required fineness. The extra fineness means that the power consumption per tonne is therefore higher for hard coals than for lignites.

The SO_2 produced by the coals will vary primarily as a result of both the sulphur and LHV contents. The following were predicted for the coals prior to FGD based on the analyses in Table 3.1:

Coal	Predicted SO_2 mg/m^3 (5% retention in ash assumed)
Taldinsky	650
Goedehoop	1325
Ptolemais	4045
Florina	4815
Drama	1100-20200

It should be noted that any changes in sulphur or LHV will have an impact on the actual levels and therefore it is expected that there will be a range in emissions for each coal. FGD plant for the lignites will need to be designed for significantly higher flue gas flow and SO_2 removal than for the hard coals. The Russian coal with 0.3% sulphur is typical for coals from the region and produces very low emissions.

The NOx emissions depend on the boiler and combustion system design as well as the fuels. Lignites have very low fuel ratios and the large boilers minimise thermal NOx production. Therefore, all three lignites would be expected to give under 200 mg/m3 of NOx as NO_2 mg/m3 dry at STP for modern lignite boilers. The hard coals, especially the South African coal, would not give NOx emissions under 200 mg/m^3 for most modern boiler designs even with overfire air. It is likely that SCR would be required

The coals also vary significantly in terms of CO_2 production. The lignites are predicted to give up to 40% more per MWh than for the hard coals and Drama lignite gives the highest emissions. The Florina is estimated to give 25% higher CO_2 than the hard coals.

2.3. Atmospheric Fluidised Bed Combustion

It is generally accepted that for optimum efficiency, fluidised bed combustors (FBC) need to be designed for a specific coal type. The FBCs are suited to lower grade fuels but at a reduced thermal efficiency. The fuel issues depend on the fluidised bed combustor type. e.g. bubbling beds, CFBC and PFBC.

Work (Ref 16) has shown that the LHV and moisture content of the fuel has a major impact on heat release in a CFBC. Applying the findings of this work to the Drama coal suggests 35% of heat would be removed in the circulating loop and 65% in backpass. For the hard coals in Table 3.1, the values are reversed: 65% circulating loop, 35% back pass. The Florina would give about 50% in each. In addition, the high flue gas flow for the lignites, compared to the hard coals, will reduce the boiler efficiency in a similar way to the supercritical boilers. Therefore, the thermal efficiency of fluid bed combustion generally decreases with increasing fuel moisture, volatile matter and ash content and with decreasing LHV. In the worst case the high moisture and ash contents may depress the bed temperature to an extent where burn-out is affected adversely.

The lignites contain significantly more ash than for the hard coals and this will impact on the ash handling systems, the ash cooling and the amount of material for landfill. The amount of ash for the lignites will be up to seven times higher than for the hard coals. The agglomerating and deposition properties of the ashes are a major issue. The hard coals are unlikely to give deposition or sintering problems providing bed temperature is controlled. However, some lignites have been shown to give calcium deposits in flue gas heat exchangers or backpass fouling. This was considered to be due primarily to finely divided calcium particles. Bed agglomeration has also been observed for high sodium lignites. The issues associated with ash properties must be investigated and addressed in the design of a CFBC for the Greek lignites. Generally operational experience on the fuels is needed because such issues are difficult to assess from fuel specifications.

The amount of limestone that needs to be added to the CFBC to reduced SO_2 depends on the coal LHV, sulphur content, calcium species in the ash and the target emission level. All coals are likely to require a Ca/S ratio of between 2 and 4, and work has indicated that a ratio of 3 is needed for the Greek lignites (Ref 16). Generally it would be expected that this level of limestone addition will give about 90% removal. Therefore, only the Drama lignite is unlikely to give under about 400 mg/m^3 of SO_2 at these removal rates. The Russian coal will require only small amounts of limestone addition to meet 400 mg/m^3 because unabated emissions are 650 mgm^3 of SO_2, i.e. only about 35% removal is needed.

The NOx emissions from CFBC boilers have been found to vary with coal type and increase with increasing: coal heat content, limestone addition and excess air. Most of the NOx produced is NO but the low temperature of CFBC boilers also results in the formation of N_2O (nitrous oxide). The N_2O is a strong greenhouse gas and is believed

to cause ozone depletion. The biggest source of N_2O is agriculture. It is possible that emission limits regulations for N_2O will be applied to CFBC plants The trend for N_2O emissions with coal type is less than for hard coals clear because emissions increase then decrease with bed temperature. The Greek lignites would give low bed temperatures (under 800˚C) and therefore both low NO and N2O although a minimum temperature for satisfactory combustion must be achieved. CFBC boilers are likely to require additional NOx removal to achieve the required emission limits.

2.4. Pressurise Fluidised Bed Combustion (PFBC)

The data on coal impacts on PFBC are from relatively few demonstration plants and from research facilities. The impact of pressure is considered to improve combustion efficiency, SO_2 removal and it reduces NOx emissions. However, the potential for sintering and blockage, especially for cyclones, is increased. NOx emissions of 200-400 mg/m^3 can be expected with lowest NOx for the lignites. More than 90% sulphur removal can be achieved with Ca/S ratios of 1.5 – 3.0. The technology has been used with black lignite with a minimum heat content 8.5 MJ/kg and ash content up to 47% and therefore for ash loadings similar to those predicted for the Greek lignites.

A major problem for PFBC is that malfunction of the coal feed system results in increased bed temperatures and the potential to cause agglomeration issues in the PFBC. Such malfunctions have occurred in the Escatron PFBC. The high coal feed compared to for hard coals, puts even more emphasis on reliable coal feeding. Another issue is the high reactivity of lignites as this may lead to fires in the feeding system. It is recommended that the feeding system is partially inerted to prevent fires.

The potential to block the cyclone ash system with sintered deposits is a major issue for unavailability. The blockage also results in increase solids loading to the gas turbine and therefore potential for increased deposition and wear of the turbine blades. The blockages will be more likely for coals with low ash fusion temperatures such as lignites.

A further deposition issues is where a hot gas filter is used, for instance where a higher efficiency gas turbine is installed. The ash properties, the calcium sorbent type and the cleaning temperature are important. Little data exists for lignites under such circumstances but it is likely that these would need reduced cleaning temperatures to avoiding sintering of ash on the filters. This would therefore reduce the temperatures to the gas turbine and therefore 'topping' by gas firing would be needed to achieve optimum gas turbine efficiencies. In general, it may be possible to use higher gas turbine inlet temperatures for hard coals but lignites are likely to require a ruggedised gas turbine operating at a relatively low inlet temperature.

The overall efficiency for Alstom's P800 PFBC has been estimated to be around 40% on a LHV basis for hard coal. High moisture fuels increase the power from the gas turbine but there is still an efficiency penalty on the steam cycle. Theoretically, a reduction of 2% points can be expected for high moisture lignites due to increased losses. But as discussed above it is unlikely that bed temperature control will be possible for the highest moisture Greek lignites. The incorporation of a pre-drying system for lignite could overcome such problems.

2.5. IGCC

Integrated combined cycles based on coal gasification vary significantly in terms of the gasifier type, gas cleaning systems, gas turbine, secondary solids combustors and configuration. The most mature technologies are the entrained type.

A key issue is feeding of the coals into the gasifiers. For lignite, a dry feed is required because of the already high inherent moisture and low heat content. Additional pre-drying is also likely to be required. In general, the low rank coals such as the Greek lignites are not well suited to the entrained flow gasifiers. These gasifiers need to achieve high temperatures and therefore use dry and fine pulverised fuels. Instead the fluidised bed gasifiers such as the High Temperature Winkler are far more suited to these coals, although the fuel requires pre-drying. The Russian and S African coals are well suited to each of the gasification processes, although there may be some issues with ash viscosity for some the slagging gasifiers because the coals have relatively high ash fusion temperatures. These coals may require some 'fluxing' agent to reduce the ash melting temperatures.

The syngas produced by coal gasifiers is highly corrosive at high temperature due to the reducing nature and presence of sulphides, chlorides and metal vapours and therefore metal component life is a significant issue. Low sulphur and low chlorine coals are therefore favoured to minimise corrosion.

Typical efficiency (LHV) for IGCC on black coal is 42-45% but it is unlikely that the leading entrained gasification-based systems could be operated with wet lignite. It is possible that these IGCC systems could be adapted to take lignites if pre-dried. This is also predicted to improve net efficiency to values close to state of the art supercritical plant with drying.

2.6. Power Plants with Carbon Sequestration

Power plants with carbon sequestration will need to remove up to 50% more CO_2 per MWh for the lignites than for the hard coals. The increased volume of flue gas from lignite plant will also increase the amount of flue gas requiring treatment but will give a similar concentration of CO_2. Overall, the impact will be increased capital and operating costs for CO_2 removal for the lignite power plants. Similarly IGCC will require increased removal of CO_2 when operated on lignite and there may be additional impact on catalyst life for the shift reactor.

Amine scrubbing plant to remove CO_2 from flue gases requires very low levels of SO_2 (< 10-30 mg/m3) to achieve adequate life of the amine. Therefore, achieving such low levels will be more onerous for the very high producing SO_2 lignites such as Drama.

2.7. Overview of Technologies

For lignites, the most developed technology is supercritical PF combustion. State of the art plant has been built and operated at commercial scale and high efficiency is possible although it is lower than for bituminous coal due to increased flue gas losses for lignites. The application of pre-drying of lignites overcomes efficiency losses due to the high moisture. FBC technology has a role for smaller (<250MW) lignite plant due to inner capital cost. However, at this scale plant will be at a lower steam conditions than supercritical PF. PFBC and IGCC technologies are still relatively unproven and the demonstration plants vary significantly in design. In both cases, pre-drying of the lignite is required for optimum efficiency and in the case of IGCC the use of pre-drying may lead to efficiencies as high as for the supercritical PF plant. In PFBC, the efficiency is likely to be lower than for IGCC and supercritical PF due to the lack of hot gas cleaning. Fluidised bed gasifiers are suited to lignite gasification although pre-drying may widen the ability to use other technologies.

3. Environmental Drivers on Supercritical Development

The increased focus on reducing emissions has driven technology development, in particular:

- Acid gases: NOx & SOx
- Dust
- CO_2

NO_x formation and control greatly affects the design of the boiler plant, whereas SO_x and dust emission control do not, due to being fitted downstream of the boiler. There are back-end NO_x control systems, but these are usually in addition to front end control measures. The requirement to reduce CO_2 emissions and resource usage has driven the development of higher efficiency PF plant. These developments have required the use of more onerous boiler design parameters (pressure and temperatures) and this has required materials development. In addition, process modifications to increase plant efficiency were added. These are waste heat recovering systems, multi stage feedwater preheating system, measures to reduce energy consumption of the plant and improvement of efficiency of components e.g. turbine, cooling tower and condenser.

3.1. Formation of NOx in the combustion process

During the combustion of fossil fuels, NO_x emissions (NO and NO_2 indicated as NO_x) are produced by the oxidisation of the nitrogen contained in the fuel and atmospheric nitrogen at high temperatures. These NO_x emissions are dependent on the adiabatic combustion temperature and O_2 concentration. We distinguish between several types of nitrogen oxides formed (Germany's Technical Association of Large Power Plant Operators – VGB / Germany's Association of Steam Boiler, Pressure Vessel and Piping Manufacturers - FDBR 1992)

Prompt NO
The prompt NO mechanism is based on the chemical reaction of atmospheric nitrogen molecules due to the attack of CH_i radicals in the primary reaction zone of hydrocarbon flames. The contribution of the prompt NO mechanism to NO_x formation is of minor importance for PF flames.

Thermal NO
Thermal NO formation is based on the reaction of atmospheric nitrogen with oxygen molecules. Due to high activation energy, a high temperature level is the precondition for NO_x formation based on this mechanism. Moreover, the required residence times are relatively long. Long residence times at high temperatures (>1,400°C) are necessary to ensure that in PF firing systems with dry ash removal this mechanism is not dominant for the formation of NO_x.

Firing systems with a very high furnace temperature like slag-tap furnaces or cyclone firing systems are no longer built today, because the portion of thermally formed NO is correspondingly higher.

Fuel NO
The major source for the NO_x emissions from PF-fired power plants can be attributed to fuel bound nitrogen conversion. The nitrogen bound in the fuel is released during pyrolysis and char burnout and converted by rapid reactions of radicals into HCN, which is converted in further reactions into NH_i compounds. Depending on the local reaction conditions, the formation of NO or the reduction to molecular nitrogen is possible. This is an important fact for so-called air staging. In this case the main

combustion zone is not supplied with the total amount of air which is necessary for complete combustion, but the primary combustion zone is operated with air deficiency. The reduction to molecular nitrogen is intensified by the lower local oxygen available.

3.2. Measures to Reduce NOx

Basically, we differentiate between primary and secondary measures to reduce NO_x emissions. Primary measures are modifications to the firing system that directly reduce NO_x emissions at their place of origin.

Secondary measures refer to plant sections that reduce NO_x emissions downstream of the actual combustion process.

The measures outlined for NO_x reduction apply to pulverised fuel (PF) firing systems for lignite and hard coal. Since the early 1970s, PF firing is state-of-the-art for large combustion plants.

The NO_x reduction measures are described below.

3.2.1. Primary Measures

The aim of primary measures is to reduce NO_x formation in the combustion process directly in the furnace, i.e. to ensure that as little NO_x as possible is produced.

Primary measures are:

- Reduction in excess air
- Air staging across combustion chamber height
- Vertical fuel staging across burner height
- Flue gas recirculation (cold flue gases downstream of air pre-heater are re-circulated to combustion chamber)
- Finer coal milling
- Low-NO_x burner: The most important design of the low NOx burner lay out is characterised by concentration of fuel and graduation of air to get a controlled combustion avoiding the production of NOx

These measures counteract the formation of NO_x. The intensity and timescale of the mixing of fuel and air is reduced, which results in longer residence times of the fuel particles within a reducing environment. Air staging across the combustion chamber height ensures that air is only supplied when it is needed for combustion of the fuel particles. This keeps the combustion temperature as low as possible. Finer coal milling reduces the size of the fuel particles and reduces the required time for burnout in the combustion chamber.

A further primary measure besides air staging is fuel staging. The reaction step for so-called afterburning is determined by the staged fuel supply.

On the firing side, factors like global and local stoichiometry and the residence time in the substoichiometric zone are decisive for the potential of NO_x reduction. Furthermore, coal properties like the amount of volatile matter, the content of fuel bound nitrogen, the behaviour of the coal during pyrolysis and the fineness of the PF are of importance.

Primary measures to reduce NO_x emissions can be retrofitted in existing firing systems/boilers. This requires a corresponding modification of the furnaces. Between 1986 and 1992, such retrofit measures have been performed in all large combustion plants in Germany.

3.2.2. Secondary Measures

Secondary measures are measures that mitigate NO_x emissions downstream of the combustion process. As a matter of principle, hard coal-fired plants require primary and secondary measures to comply with the stipulated emission limit values in Germany. Hard coals have higher calorific values, and therefore higher adiabatic combustion temperatures resulting in higher NO_x emissions.

Secondary measures involve ammonia injection (SNCR Selective Non Catalytic Reduction) and the use of catalysts and can be fitted upstream or downstream of the airheaters and electronic precips, "high dust" and "low dust" respectively. SCR (Selective Catalytic Reduction) catalysts have been generated successfully in both high and low dust situations. This technology is described later in Section 7.

3.3. New Plant Firing Systems

3.3.1. Lignite Firing Systems

Lignite firing systems for utility boilers are mostly designed as tangential firing systems. One mill feeds one burner group.
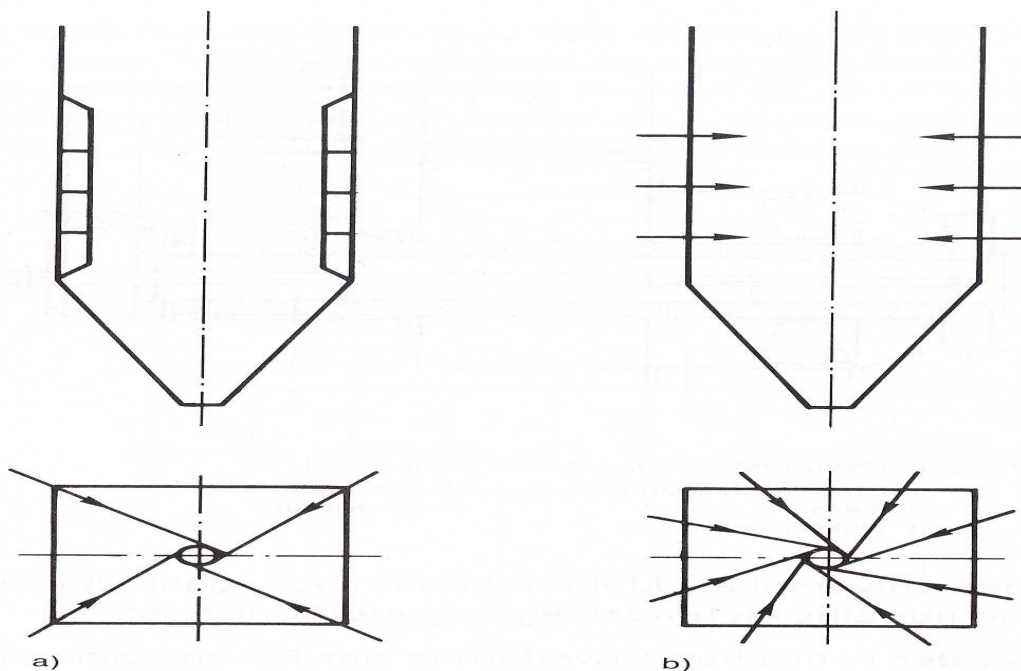

Abb. 4.34. Tangentialfeuerungen.
a) Eckenfeuerung mit je 1 Mühle
   für eine Brennerebene
b) Umfangsfeuerung mit je 1 Mühle
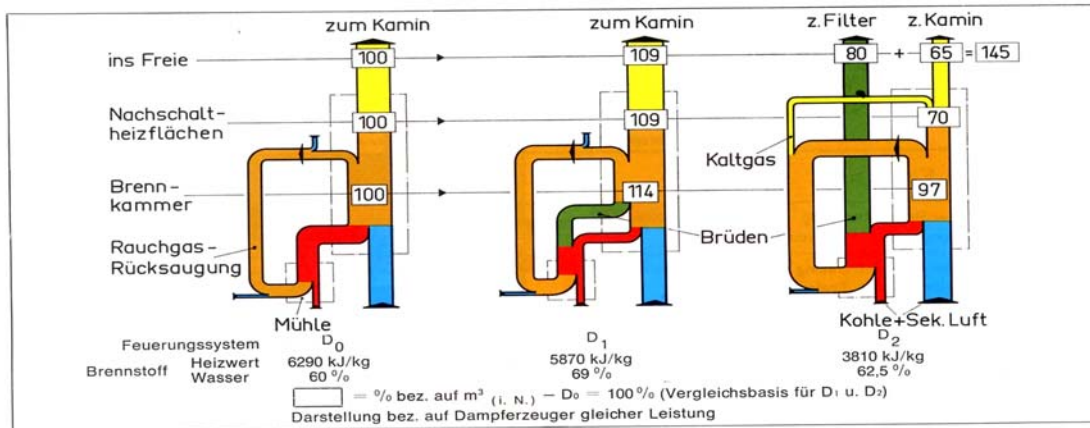   für mehrere übereinanderliegende Brenner

Figure 2:

Bild 13
Vergleich der Gasvolumenströme
bei Feuerungssystemen mit direkter Einblasung

Figure 3:

Due to the high moisture content of lignite it is necessary to use re-circulated flue gas at high temperatures (approx. 1,000°C) from the furnace exit to dry the lignite to a residual moisture content of around 20%. Therefore the lignite mills are designed as hammer wheel mills to transport the flue gas and to mill the lignite which is softer than hard coal. Re-circulating flue gas has the advantage that the milling cycle is operated with inert gas which reduces the risk of fires and explosion.

3.3.2. Hard Coal Firing Systems

Hard coal firing systems use hot air to dry the coal which has significantly lower (<15%) moisture contents than lignite. The technology used to grind hard coal calls for mills with a high, adjustable grinding force to pulverise the hard coal and requires hot air for drying and pneumatic conveying. Typically these are medium speed vehicle spindle mills or ball-in-race or fixed. Hard coal has to be pulverised to finer size fractions than lignite. Due to the higher carbon percentage of the particles, this is necessary to ensure burnout at the end of the furnace.

In general, the volatile matter percentage determines the fineness of the size fractions required, i.e. lower volatile coals need to be ground finer. Direct and indirect firing systems are feasible. The most common designs are tangential or front wall firing systems. One mill feeds one burner level.

Firing systems with slag-tap furnace were designed for handling hard coals with low volatile matter i.e. anthracite, to ensure safe operation of the firing system, owing to the high combustion temperatures, resulting in high NO_x emissions, these systems are generally not used for present designs of boilers.

The standard pulverised firing system for hard coal fired boilers is with low-NO_x burners fitted.

3.3.3. Impact of Coal Specification

Imported coal is available from different geographical (and hence geological) sources. The design of a specific firing system depends on the fuel characteristics of the imported coal.
The main properties that affect firing system design are:

- Volatile matter
- Grindability, Hardgrove index
- Ash content
- Moisture
- Net calorific value
- N_2 content
- Ash analysis

Significant variation in the fuel properties may require an adjustment of the operating conditions of the firing system and the mills.

3.4. Retrofit of existing plants

In Germany NO_x emissions were reduced by modifying the firing system and optimising control and peripheral systems. The results could not be exactly forecast at the time when the modifications were planned because exact calculation methods were lacking. Variable factors included the nitrogen in the fuel and the adiabatic combustion temperature. Therefore the strategy was to implement the modifications and correct the measures after empirical improvement.

The development of methods for computer simulations and recalculation of algorithms to describe combustion allowed forecasts to be generated for the behaviour of firing systems. This method; which is based on the individual conditions prevailing in existing plants and on actual operating data, allows reliable forecasts for planned modifications to be made. In addition, first optimisation steps can be simulated, so that preliminary optimisation is possible before commissioning. This enables an effective and short implementation period and the evaluation of optimisation options for commissioning.

With regard to possible investigation for the PF firing system, for the evaluation of combustion, emission values, temperature distribution and contamination forecast, computer simulations methods can be applied. For validation of the simulation the measured data and results from before modification are used to verify the basic variant of the simulation system.

Using these methods, costs and time spent on modifications, commissioning and optimisation can be minimised and plant outages for the modifications reduced (Refs 12, 13, 14)

From our experience we can verify that using this services is an advantage. Proposed concepts for measures to reduce NO_x emissions can be checked and the best solution can be identified. This supports the decision with additional facts, avoids empirical improvement and shortens project schedules.

3.4.1. Primary measures for Retrofitting Firing Systems

Changes to the existing firing system in order to reduce NO_x emissions can be made by modifying the burners, secondary air system, additional flue gas recirculation system and reducing excess air for combustion.

Additional peripheral systems have to be adjusted; e. g. the burner and mill system must be optimised to reflect the changed flow resistance in the burner ducts and outlets to the furnace. To achieve similar combustion results and keep the unburned carbon within an acceptable range, the pulverising systems (mills) must be optimised.
Therefore isokinetic sampling of pulverised coal from the burner PF pipes and flow rate measurement have to be performed to ensure PF quality and distribution are

acceptable.

3.4.2. Retrofitting Lignite Firing Systems

Based on the experience with primary NO_x reduction measures, there are three feasible firing systems.

- Direct combustion with reduced burner belt height resulting in a more concentrated fuel area and separated air staging.

  This concept is above all appropriate for large steam generators with long residence times in the combustion chamber.

- Direct combustion with reduced burner belt height resulting in a more concentrated fuel area and separated air staging combined with additional flue gas recirculation.

  This concept is the most variable and can be used for all sizes of steam generators. In flue gas recirculation, cold flue gas is re-circulated from downstream of the ESP and injected into the furnace via separate nozzles arranged above the burner belt. This increases the mixing of the reactants even in the case of short residence times. Combustion burnout is delayed by the addition of the flue gas.

- Modified vapour burner concept. Direct combustion with a vapour separator downstream of the mill to divide the fuel/carrier gas mixture to the main and vapour burners and air staging across the combustion chamber height.

  In addition to reduced burner belt height, centrifugal separation of fuel and carrier gas also increases the fuel/carrier gas ratio. Via the vapour burners, the carrier gas with a low fuel concentration is injected into the combustion chamber, the effect being similar to that of flue gas recirculation.

The furnaces of existing lignite-fired steam generators can be converted to low NO_x mode by Primary measures meeting the statutory emission limits for NO_x of 200 mg/m³ STP related to 6% O_2.

Following the conversion of existing furnaces in Germany, individual optimisation was required in all plants. This optimisation was made empirically. The firing system conditions are more onerous and small changes in the air distribution and other operational settings of the plant can have serious implications for the NO_x emission behaviour.

3.5. Retrofitting Hard Coal Low-NOx Firing Systems

Firing systems for hard coal were modified to reduce NO_x emissions on a similar basis as for lignite firing. Starting from a higher initial value of NO_x emissions, additional measures were necessary i.e. newly developed low-NO_x burners and SCR catalysts as described later.

Modern firing systems are designed for low NO_x emissions by using air and fuel staging, high PF fineness low-NO_x burners with substoichiometric operation mode as primary measures. In order to prevent furnace wall corrosion, due to a substoichiometric operation mode, special measures have to be taken to ensure sufficient oxygen concentration to avoid very high CO concentrations at the walls.

The nature of the unburned carbon in the fly ash and the CO concentrations, in particular near the walls, have to be investigated during the firing system optimisation. Despite the low NO_x emissions, values well below 5% carbon in ash should be achieved.

For further NO_x reduction, the High-Dust Selective Catalytic Reduction as described later is the state-of-the-art technology used to reach the NO_x emissions below the LCPD required levels for hard coal.

4. State-of-the-Art Lignite Fired Power Generation Technologies

In the following chapter, the state of the art technology for lignite power stations is described. They are:

- The BoA technology, which stands for: "lignite fuelled power station with advanced plant technology".
- The BoA plus technology, which stands for BoA with application of a firing system by using pre-dried lignite.
- Gas turbine re-powering, by combining a lignite fuelled unit with a gas turbine, to increase efficiency and generating capacity of an existing unit.

The boilers had been conceived as draw-in boilers into tower building method.
This construction resulted from experiences of many years with brown coal and offered the best wear protection for heating surfaces, which encounters with the ash-loaded flue gas. For the reason of the tower building method all detours within the flue gas range of eco- and superheater heating surfaces were avoided.

In the 80's the desulphurisation plants, those which belong today to the standard equipment of a power station block, have been planned, developed and put into operation. In the meantime sufficient experiences are present concerning corrosion protection of the absorbers and treatment of the exhaust gases, in order to develop economical and concepts reliable in service.

In the 90's firing attempts were driven, and burner construction developed, in order to adapt the NOx emissions of lignite unit to legal requirements.

The low calorific value and the relatively large, specific flue gas quantity generally make possible a coal dust burner enterprise with low firing temperatures.
This advantage of brown coal was utilized in order to arrange the flame development with an appropriate fuel and air circulation, so that at a low burn temperature with under-stoichiometric burn within the burner range the NOx education could be reduced very strongly. To affect the burn guidance better, the comminution of mills has been improved. The relatively rough and economical comminution with coarse grain portions of partially 10% and more than 1 mm of grain size, depending on type of mill and wear, was entitled to values under 5% and reduced over 1 mm.

Therefore the burn-out condition of the flame was substantially shortened and the possibility of the purposeful air dosage was substantially improved.

With a following supply of hangfire air within the upper range of the combustion chamber, CO, which arised with the under-stoichiometric combustion, oxidized to CO_2.

The operational experiences with the new NOx poor firings brought as good results that it could be done without installation of catalysts as usual in hard coal. Also the

injection of ammonia was not necessary for transformation of the already formed NOx.

For the new planning of brown coal blocks already two concepts for the solution of emission problems had offered themselves that way. The CO2 decrease turned out as next requirement of environmental protection.

Since the carbon content in the brown coal cannot be reduced by a pre-treatment as e.g. by coal drying process, there are only two procedural possibilities.

- The one exists in a flue gas scrubbing similar to the SO_2 reduction in the wet scrubber. This possibility is very complex and cost-intensive with the available flue gas volumes and is examined in another concept of RWE at present.
- The other possibility consists of the increase of the block efficiency, which in this way leads to the reduction of the entire amount of fuel and concomitantly to the specific CO_2 decrease.

With the development of the BoA concept RWE has gone the second way. All components and systems of the power station, not only the boiler range were submitted of an examination regarding an efficiency increase.

Thus within the turbine range the new technology of the 3D shovels and the interpretation of the low pressure part were used on a very low condenser pressure for efficiency increase, the advancement of materials within the high temperature range permitted an increase of the process parameters, which likewise lead to an efficiency increase of the total process. The feed water preheating unit was optimized by tapping of the high pressure turbine and by an increase of the numbers of preheaters on ten stages. The exhaust gas temperature behind the Luvo was continued to reduce by a heat replacement system system and so the boiler efficiency was improved. Also the internal requirement could be reduced by detail optimization so that the next efficiency of the brown coal block could be increased altogether to 43%. Since for competition reasons the economic side could not be ignored, the plant size is optimized regarding the specific cost degression and for the BoA concept an achievement size of approximately 1100 MW. clamp capacity of the steam turbine determines. The plant BoA 23 emanates from a double block, which shaped up as cheaper compared with the single block plant and represents a proven RWE concept for a long time.

The BoA Plus plant is a further step in the direction of CO_2 reduction on basis of BoA power station technology. It is connected probably in the range of the treatment of fuels and firing with a change of system, which must persist its operating probation still in a large-scale installation. However, it offers a potential, which transcend the bare efficiency increase of the power plant and develops new application for the insert of heat value poor and aqueous.

A further possibility of CO_2 decrease is endowed in a change of fuel. By admixture of natural gas to the brown coal fuel in a power plant, the carbon portion is reduced and replaced it by hydrogen out of the natural gas, so that the fuel warmth has altogether a smaller CO_2 but a higher H_2O portion.

This concept is plantspecific realized by the employment of a connecting gas turbine.

The coupling of the gas turbine to the coal block takes place over the water steam side of the coal block. The integration of gas turbine exhaust heat with the firing system of the coal block has been examined and implemented. However, this system did not work.

Therefore RWE merged the waste heat of the gas turbine over a waste heat boiler into the condensate system of the coal block.

In this way it gains a fast available power reserve by connecting the gas turbine, an increase of the overall efficiency and in this way a double reduction of CO_2 emission by efficiency increase and natural gas employment.

From economic view the employment of the gas turbine depends on the natural gas price and attainable price for peak load stream.

The description of the BoA power station technology, described here to the Greek coal, depends on the firing behaviour of Greek coal with the substantially lower heat value. The frame technology of the BoA technology is easily transferable, in the boiler range however is necessary appropriate detail investigations, which necessitate an adjustment meal and firing system.

The fundamental plant concepts however might be transferable.

4.1. BoA as Demonstrated by the BoA 2/3 Project in Neurath

RWE Power is continuing the renewal of its power plant portfolio with ultra-modern and less polluting technology, investing €2.2 billion, – including an investment in the future of the Rhenish lignite mining area.

Figure 4: Schematic figure of the BoA 2/3 project in Neurath, Germany

In June 2005, the Düsseldorf regional government gave its approval for the construction and operation of two lignite-fired power stations with the optimised plant technology (BoA) at Neurath.

After the Niederaussem-based "first-of-class", which commenced operation in 2003, the new units will be the 2nd and 3rd (BoA 2/3) with this modern design.

RWE Power started site preparatory work immediately and, in September 2005, decided to construct the twin unit.

The Company will be investing €2.2 billion. The decision assumed that the current arrangements emission rights for new and replacement plants will continue to apply after 2008 within the scope of the so-called (CO_2) National Allocation Plan 2.

The construction work will take about four years, so that the start of commercial operation can be expected in approx. 2010.

Key

1) Unit transformers
2) Switch house
3) Turbine house
4) Steam-generator enclosure
5) Electrostatic precipitator
6) Flue-gas cooler
7) Flue-gas desulphurization plant
8) Cooling tower
9) Slot-bottom bin
10) Ancillary systems

North

BoA 2/3 – bottom left:
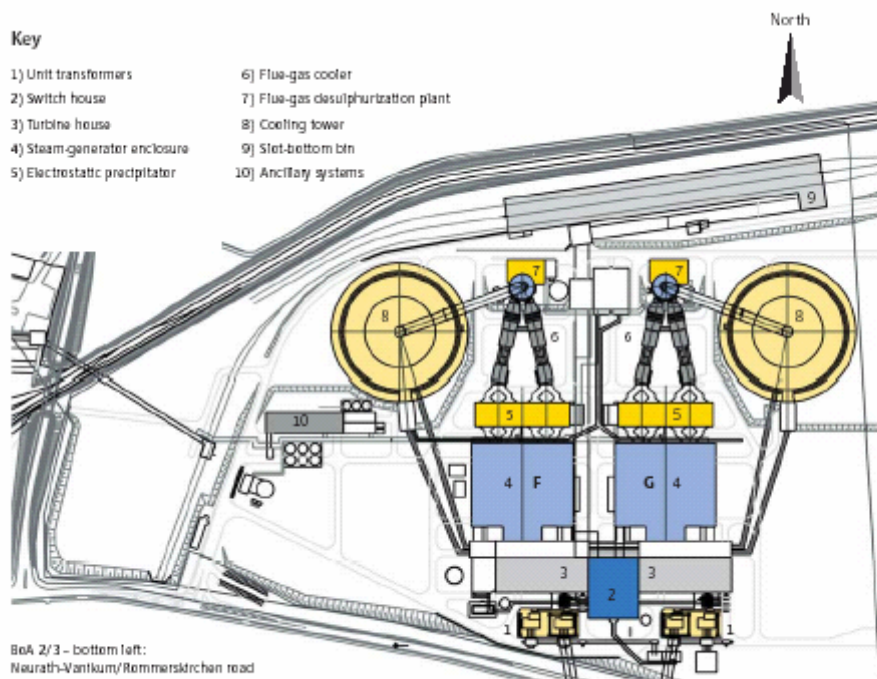Neurath-Vanikum/Rommerskirchen road

Figure 5:

Figure 6:

The two power plant units will have a gross capacity of 1,100 MW each and an efficiency of over 43%. The most striking components are the two buildings for the steam generators (boilers), which will look similar to the Niederaussem unit, and the two cooling towers.

The structures will be some 173 m high. The operational area of the two new units comprises just under 37 hectares (ha). Of this, less than 50% is built on. As an ecological offset for the erection of the two new power plant units, including rail track linkup and overhead lines, RWE Power will reforest some 23 ha of farmland in the area of Neurath, Sinsteden and Vanikum in accordance with a concept agreed with the municipalities affected and with the landscape authorities. In addition about 10 ha of cultivated land which, thanks to a special farming method, will offer grazing livestock species in particular a safe and healthy environment.

Before commissioning the first new BoA unit, RWE Power will shut down six 150MW units at the Frimmersdorf power plant. A provision to that effect forms part of the approval notification of the Düsseldorf regional government dated 20 June 2005. In a period of some two years after the start of commercial operations at the new power plant units, four more 150MW units at Frimmersdorf or Niederaussem are to be finally decommissioned. Two further 150MW units are to follow in the same period if the supply situation in RWE's grid permits this. The 150MW units are old some dating back to the 1950's and so are relatively low efficiency and so have higher specific emissions.

4.1.1. The BoA units F and G

Following on from the designation of the existing power plant units at the Neurath location, the BoA units will be named "unit F" and "unit G". The two new units will be erected on the site east of the existing Neurath power plant and partially connected to the supply and disposal facilities of the existing plants, which must in part be retrofitted or extended for this purpose.

For lignite supplies, a new coal yard in the form of a subterranean slot-bottom silo is being built. The raw lignite is delivered to the new silo using the Company's own north-south railway from the Garzweiler and Hambach opencast mines. From there, the lignite is transported by a new conveyor belt system to the day silos in the boiler houses.

Energy conversion

| Chemically bound energy | → | Thermal energy | → | Rotational energy | → | Electric energy |

Lignite

Steam generator　　　　Turbine　　　　Generator　　　　Pylon
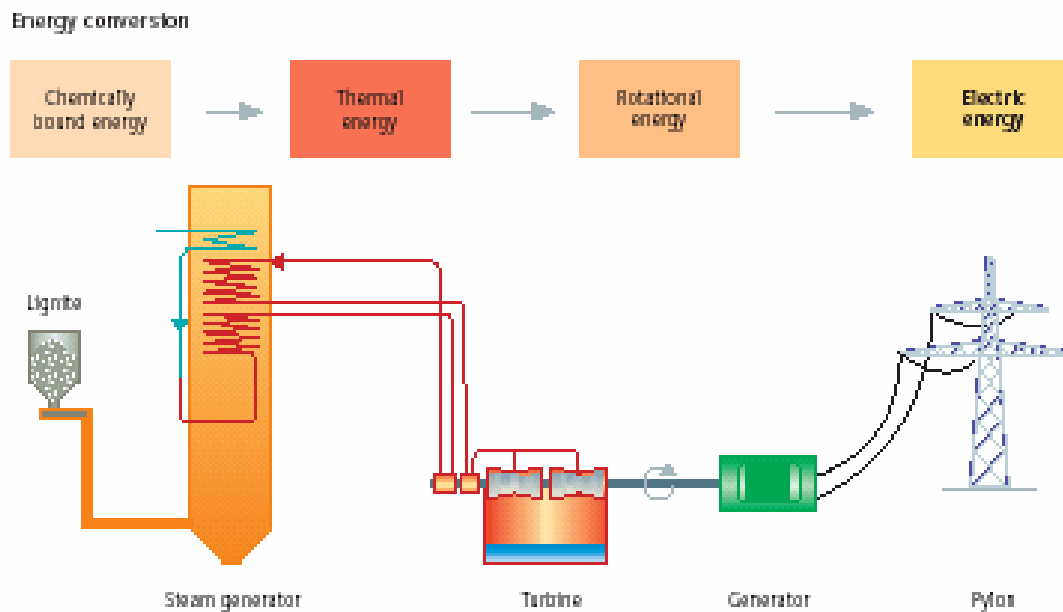
Figure 7: The Energy Conversion from Coal to Electricity

The principle for the new power plant units is to be highly automated with monitoring from a central control room. Regular servicing, preventive maintenance and rotating plant overhauls are designed to enable high availability.

Although the BoA units basic design principles are similar to existing plants, they incorporate the best technology available today for converting lignite into electricity due to numerous detailed improvements.

The result is the enhanced use of the input fuel and, hence, even more environmentally friendly power generation than in the older plants. Therefore the efficiency is some 31% higher than the efficiency of the oldest operating units.
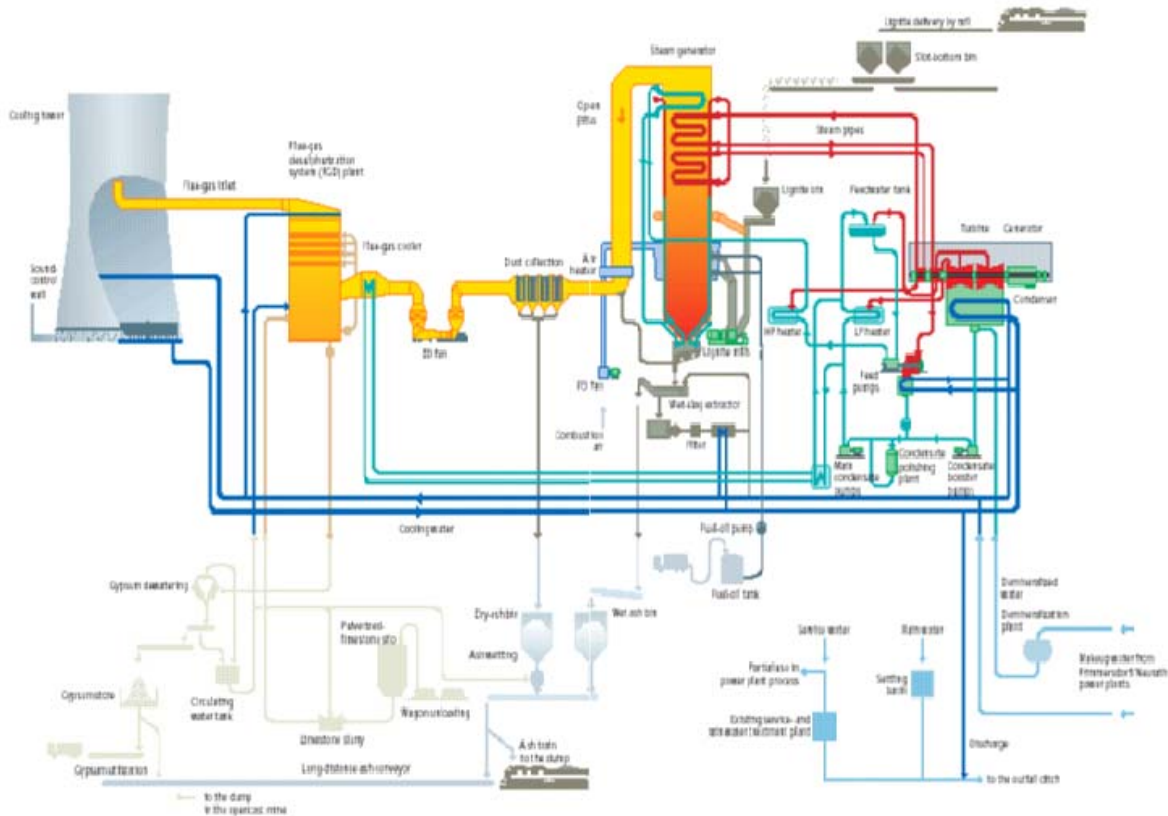
Figure 8:

4.1.2. Fuel supply

The raw Lignite from the Hambach and Garzweiler opencast mines will be transported by rail to the power station. There, it is placed on an intermediate stockpile. A conveyor belt system transports the lignite via a iron separation unit and a pre-crusher to the eight silos in the boiler house. From there it is fed into the associated lignite mills via feeder belts and chutes.

4.1.3. Milling and firing system

The mills pulverize the lignite and dry the fuel to a moisture content of 48-60% using hot flue gases taken from the furnace. Then combined with air heated by the flue-gas air heater, it is blown into the furnace of the steam generator and burnt. Combustion is constantly monitored so that the lignite and air mass flows are optimal for minimising the production of nitrogen oxides (NO_X).

The 200mg/Nm³ NO_X limit can be reliably achieved without the need for SCR.

The lignite is burnt at temperatures of about 1,200°C. The hot flue gas that emerges during combustion flows upwards through the steam generator transferring heat to the outer walls formed by tubes and to the tube banks suspended in the flue-gas flow. Heated feedwater flows through these tubes and is evaporated and superheated.

Beyond the top-most bank of heating surfaces, the flue gas is directed downwards through the open-pass ducts across the two flue-gas air heaters. After flowing through these heat exchangers, the flue gases, cooled to approx. 160°C, are ducted in two parallel lines to the flue gas cleaning system (dust collection and desulphurisation).

top. In the process, it transfers
er walls formed by tubes and
nks suspended in the flue-gas
edwater flows through these tube
steam generator and is evaporated
d by this heat absorption.
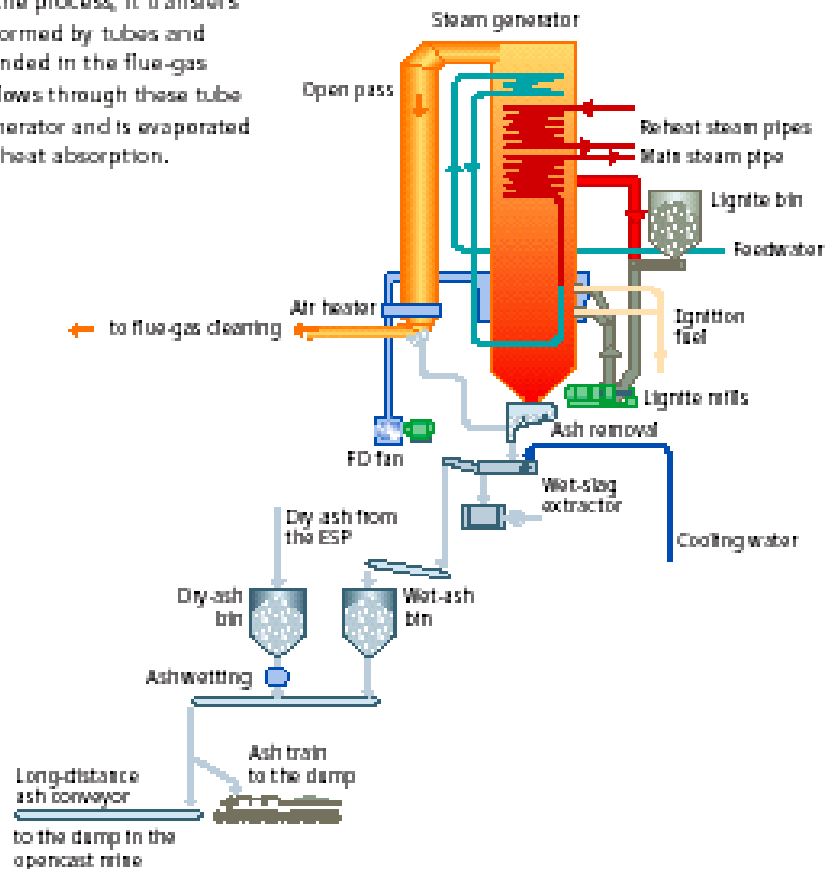
Figure 9:

4.1.4. Turbine system

The main steam produced in the steam generator has a pressure of 272 bar and a temperature of 600°C and is initially expanded to 55.5 bar in the turbine's high-pressure section, and the temperature falls to 356°C. This steam is conducted back to the steam generator and superheated again to 605°C in the reheater.

In the intermediate and low-pressure turbine sections, the steam expands to a pressure of 48 mbar (absolute) in the condenser

Water-steam cycle

turbine shaft, setting it in rotation.
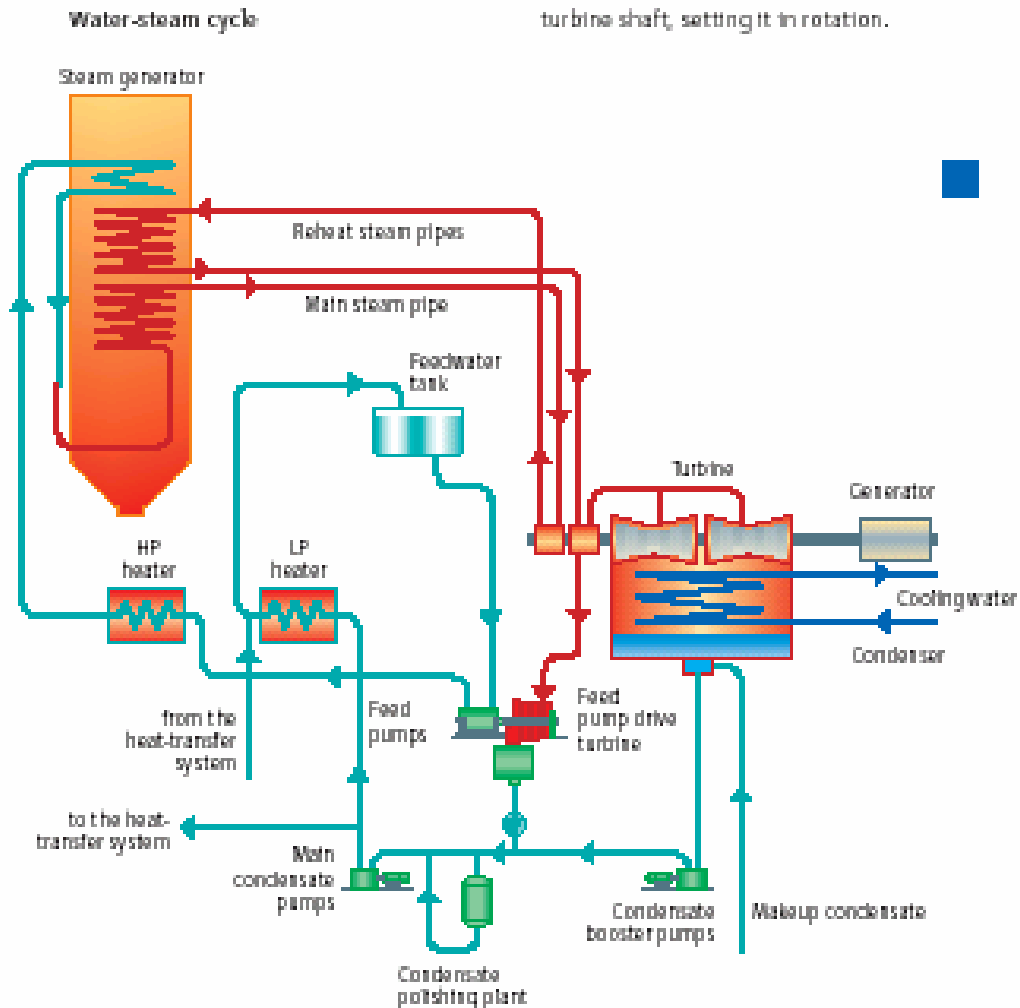
Figure 10:

4.1.5. Power Generation

The rotational energy of the turbine shaft is converted into electric energy in the connected generator. In a magnetic field between generator rotor and generator stator, electricity is produced on the induction principle. An unvarying speed of 3,000rpm ensures the standard frequency of 50 Hz for connection into the grid. The generated electricity's voltage is increased via transformers to 380KV.

4.1.6. The cooling cycle

The condenser condenses the expanded steam as water; this releases physically the latent heat of condensation, which the cooling tower discharges into the atmosphere with the aid of the circulating cooling water. The cooling water, cooled in the cooling tower flows through the pipes of the condenser, generating the desired negative pressure of 48 mbar.

The heat released in the condenser each second warms up more than 23tons of cooling water by about 12°C. The cooling water is cooled in the cooling tower by falling as a "rain" and by continuous contact with the cooling air. The air required for this working requires a 170m high cooling tower using the energy saving natural-draught principle.

The cooling water that evaporates during cooling and the cooling water that must be

discharged to avoid excess concentrations of salt must be replaced on a continuous basis. For this, use is made primarily of makeup water from the Frimmersdorf power plant which is treated there before it is deployed in Neurath. By way of an alternative, the new units can also be supplied with treated water from Niederaussem.
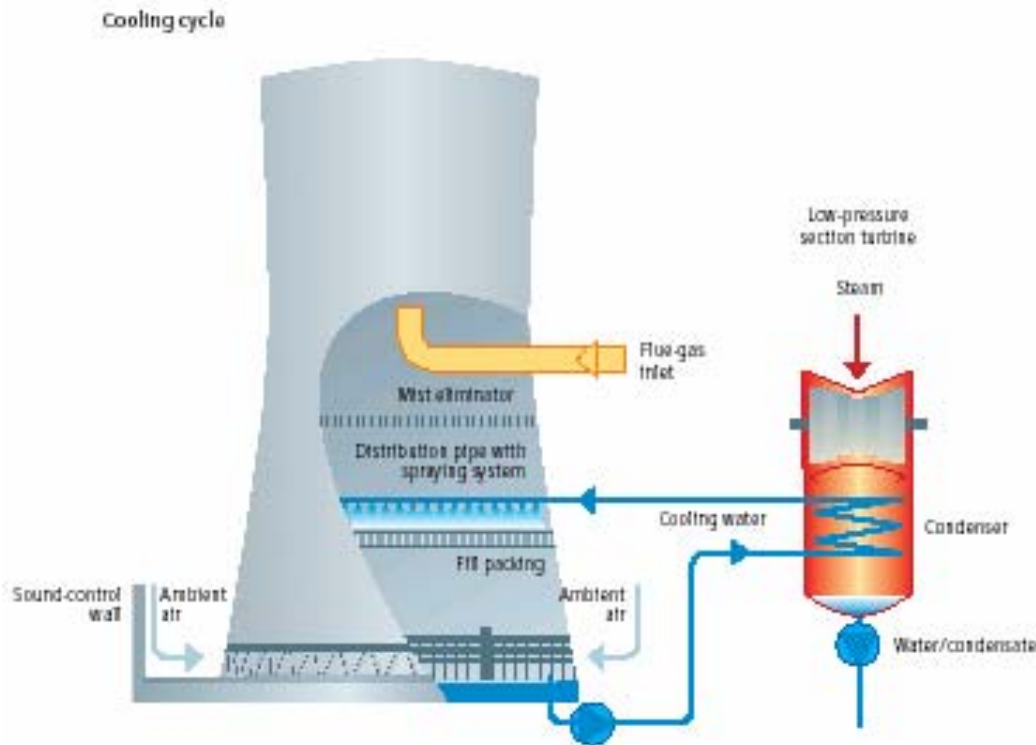
Figure 11:

4.1.7. Heat utilisation

Heat-utilisation systems ensure that the highest possible amount of the heat arising in the combustion of lignite is integrated into the process and exploited in power generation. The flue gas, for example, which leaves the steam generator at approx. 350°C, is used to heat the combustion air in two parallel air heaters. The temperature of the flue gas after it has flowed through the air heaters is about 160°C.

A further portion of the remaining flue-gas heat is removed from the flue gas before it is fed into the desulphurisation (FGD) plant via flue gas coolers and transferred via a heat-transfer cycle to a part-flow of the condensate in the feedwater heating section. This lowers the flue-gas temperature to 125°C before it enters the FGD.

4.1.8. Environmental Protection

CO_2 Emissions

One crucial objective of the new power plant units is a reduction of CO_2 emissions in electricity generation. Since no industrial-scale and commercial solutions, like filters, separators and similar, are available as yet to retain CO_2, reductions can only be achieved at present by better utilisation of the input fuel in the power plant process, i.e. by an increase in efficiency.

With an efficiency of more than 43% compared with about 31% for old systems, the BoA units meet this goal. After the corresponding old plants are decommissioned,

annual CO_2 emissions will fall by some 6 million tons. Besides CO_2 emissions, the specific SO_2, NO_X and dust emissions, too, will be reduced by some 31%. To restrict the emission concentrations in the flue gas to at least the limit values prescribed by the local regulations.

SO_2 – 200 mg/Nm³ and a sulphur reduction of min. 85%
NO_X – 200 mg/Nm³
CO – 200 mg/Nm³
Dust – 30 mg/Nm³

These limit values comply with Directive 2001/80/EC of the European Parliament and of the Council dated 23 October 2001 on the limitation of certain pollutants into the air from large combustion plants.

Figure 12:

4.1.9. Gas and Dust Emissions

Due to the design of the lignite firing system (above) the formation of nitrogen oxide and carbon monoxide is minimised. Ultra-modern electrostatic precipitators separate more than 99.8% of the dust in the flue gas. Over 90% of the sulphur dioxide from the flue gas is separated by the FGD plant using limestone which is turned into gypsum. For flue-gas desulphurisation, planning requires a wet limestone process which, besides sulphur dioxide, also removes hydrogen chloride and hydrogen fluoride from the flue gas.

Flue-gas cleaning
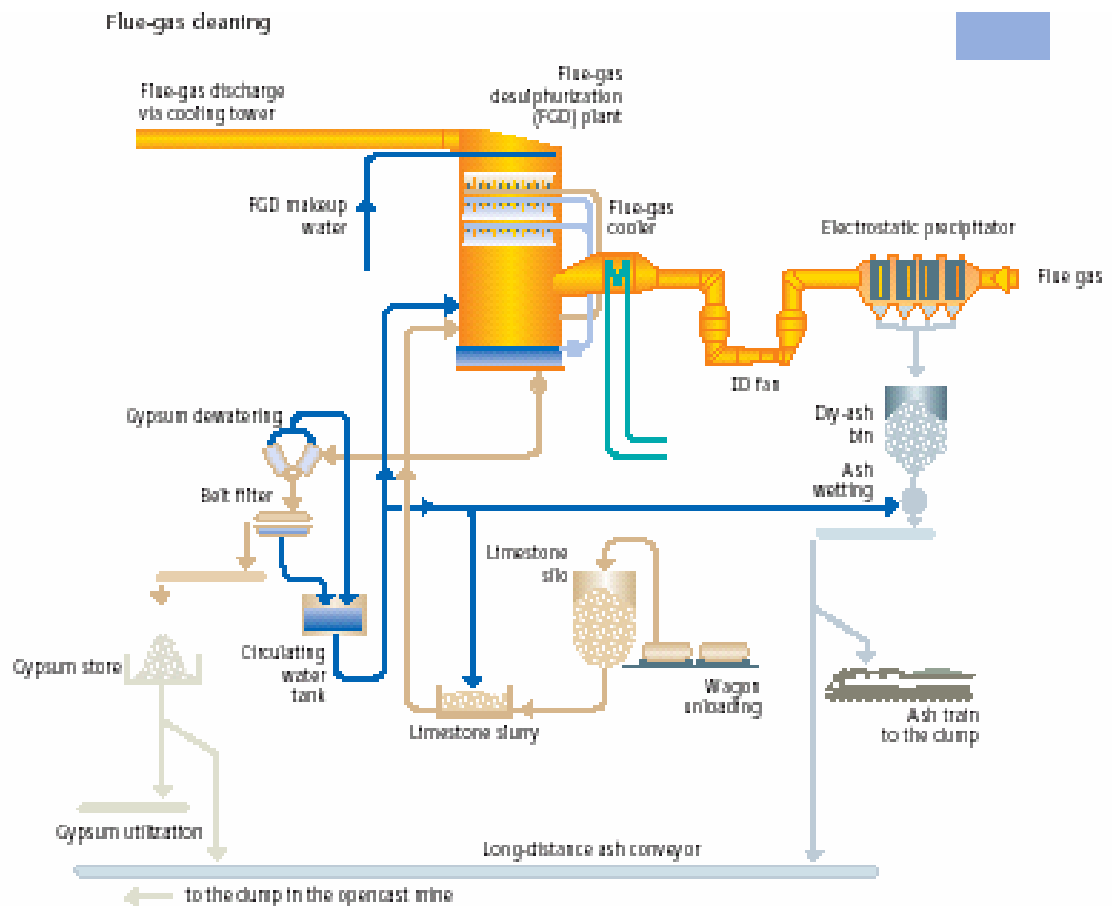
Figure 13:

4.1.10. Noise control

Where practicable, all mechanical equipment in the new power plant units is installed in enclosed rooms. Within the plants, selective sound-proofing is used to ensure a safe working environment. Firstly, low-noise machinery is used and, wherever this is not sufficient, additional sound-proofing enclosures or structural partitions are provided. For the air inlets and outlets of the buildings, silencers are fitted. To limit the noise emissions from the cooling towers, which is mainly produced by the water raining into the bottom section, the erection of sound-control walls outside the cooling towers is proposed, this enables the plant to meet the statutory noise emission levels in the local vicinity.

4.1.11. Water management

The water needs of a power plant unit are determined mainly by the evaporation losses when the heat is discharged in the cooling tower. In addition, to avoid any critical salt concentrations, some of the cooling water must be continually removed from the cooling cycle and replaced. Some of the removed cooling water can be used to meet the water needs of other plant systems (e.g. FGD), while excess amounts are directly discharged into the outfall ditch.

For service water, the existing water purification plant has sufficient cleaning capacity. The purified water is released into the outfall ditch. Any surface water is initially collected in a rainwater settling basin and then released into the outfall ditch.

4.1.12. Waste

For process-related reasons, a power plant mainly produces dry and wet ash and gypsum as waste. Some of the gypsum is sold to the construction material industry for further use. Due to the variations in gypsum quality caused by the strongly fluctuating ash composition, and the lack of market demand, some of the gypsum is used together with lignite ash for back-filling in the mine.

For the other process-related waste substances produced, re-use in the process is planned, e.g. the calciferous sludge from water treatment, for example, is used to reduce pulverised-limestone needs in flue-gas desulphurisation.

4.2. BoA plus (firing with pre dried lignite)

Power plant development is increasingly determined equally by the importance of efficiency increase and emission reduction, and economic efficiency based on the lowest possible investment and operating costs and high availability. This requires innovation development as in the case of lignite pre-drying.

4.2.1. Pre-Drying

Lignite pre-drying has been developed by RWE Rheinbraun to a level that enables significant further improvements in the lignite-based power plant process efficiency cost effectively.
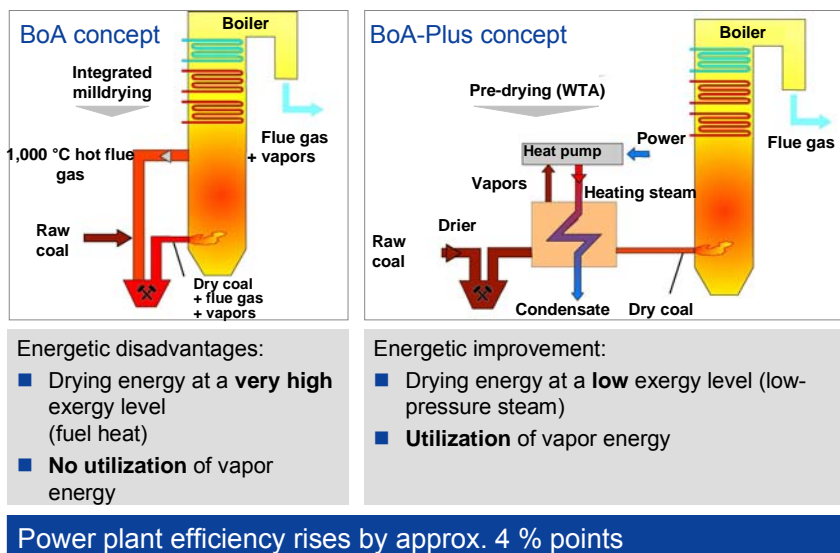
Figure 14: Coal Drying - the Key to Efficiency Increase

The process of integrated milling and drying used in the large pulverized lignite-fired power plant units is not the best solution thermodynamically but has been the most economic Separate drying systems using low-temperature heat had been uneconomic so RWE RHEINBRAUN decided to develop a new drying process, the so-called 'Wirbelschicht-Trocknung mit interner Abwärmenutzung' (WTA which stands for fluidized-bed drying with internal waste heat utilization) (Ref 2) technology.

The development of this drying process constitutes a breakthrough as in combination with the BoA technology to implement the so-called BoA-Plus (Ref 1) power plant allows a considerable rise in efficiency cost effectively so that competitiveness can be maintained or even improved. The resultant plant configuration is called BOA-Plus.

4.2.2. The Development of Pre-Drying

The first successful milestone in the course of drying development was the construction

and operation of the WTA process-based demonstration plant at Frechen.

WTA demon. plant	Pilot drying plant	WTA fine grain drying plant
Frechen	Niederaussem	Frechen
1993 - 1999	2000 - 2002	2000 - 2003

53 t/h raw coal	170 t/h raw coal	30 t/h raw coal
Coarse grain drying, operationally mature on an industrial scale	Scale-up demonstration	Breakthrough in terms of ■ simple, robust technique ■ low investment costs

Figure 15: Development Steps of WTA Technology

The WTA technology is the drying process for raw lignite integrated with the plant cycle to use the drier vapours [Refs 3 to 5].

The process has the following features:

- Drying in a stationary fluidized bed with superheated steam

- Supply of the drying energy via heat exchangers installed in the drier

- Use of drying vapours by means of a heat pump process for drier heating

- Use of the vapour condensate for coal or condensate preheating in the power plant

- Feed grain size of raw coal 0-6 mm (coarse grain drying).

This demonstration plant had an hourly raw coal input of 53 tonnes and was successfully tested from 1993 to 1999. In this period, the technical feasibility, reliability and industrial-scale maturity of the WTA technology were demonstrated using coarse grain drying. This development step was followed by the construction of the pilot drying plant based on this WTA process, designed for an hourly lignite input of 170 tonnes and located within the Niederaussem power plant complex. Its construction was completed in August 2000 and represented a scale-up of approx. 3.3 compared to the first WTA plant. This Niederaussem-based pilot plant was primarily aimed at testing the process and the plant equipment under conditions more typical of modern power

plants. Important, development issues which had not previously been resolved were clarified. The ability to scale-up the design successfully was confirmed.

In parallel with Niederaussem activities, RWE Rheinbraun has continued using the WTA plant at Frechen, with the objective of refining the process engineering. Based on the experience obtained, the process was re-structured to produce a more efficient, simple, robust and inexpensive plant. This development work has resulted in the new WTA fine grain drying technique (Ref 6).

4.2.3. Fine Grain Drying

WTA fine grain drying comprises two process steps: fine grain milling of raw coal carried out for the first time and actual fine grain drying in the fluidized bed. The two process steps were successfully tested in a test plant which had been constructed directly beside the existing WTA demonstration plant. The new plant was integrated into the infrastructure of the WTA demonstration plant.
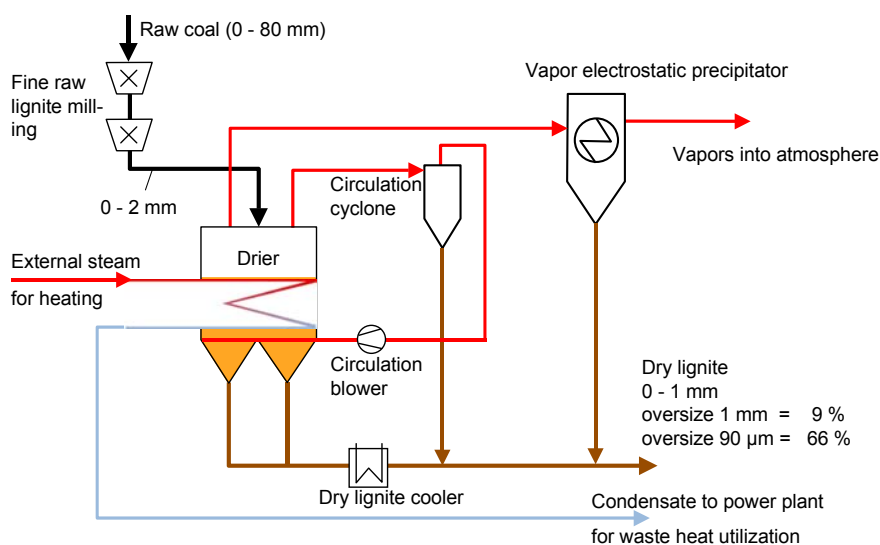
Figure 16: WTA Fine Grain Drying at Frechen, Process principle

Fine grain milling of raw coal is done in a system of two double-rotor mills directly connected in series where the coal is milled from 0 – 80 to 0 – 2 mm.

The thermal and mechanical loads to which the coal is exposed in the fluidized-bed drier have another reducing impact on the grain size so that the dry coal (12% moisture) leaving the drier has a grain size of 0 – 1 mm, with oversize at 1 mm amounting to approx. 9% and that at 90 µm to approx. 66%. Depending on the combustion requirements in the steam generator, further secondary milling of dry lignite can be totally dispensed with, or it can be confined to a very simple system. This, too, is a decisive progress compared with coarse grain drying that called for a very sophisticated and expensive dry lignite milling system. The coarse grain drying would have produced a grain size of 35% above 1 mm and 85% above 90 µm.

The fluidized bed is fluidized in the drier by means of a partial quantity of the vapor leaving the drier which is then circulated by a blower and only coarsely separated from dust in a cyclone. Thanks to the use of raw coal with a very fine grain size, the vapor amount required for fluidization of the fluidized bed in the drier is lowered by approx. 70% compared to coarse grain drying employed so far.

Performance data, drying*

Circulation blower, vol. flow rate	ESP, vol. flow rate	Vapor compressor, no. of stages	Drier, construct. height
- 66 %	- 50 %	- 33 %	- 53 %

Spec. investment*

- 60 %

€70/KW

Industrial-scale plant for 1,050 MW_n BoA-Plus variant

* Initial values (100 %) = coarse grain drying with the same rating
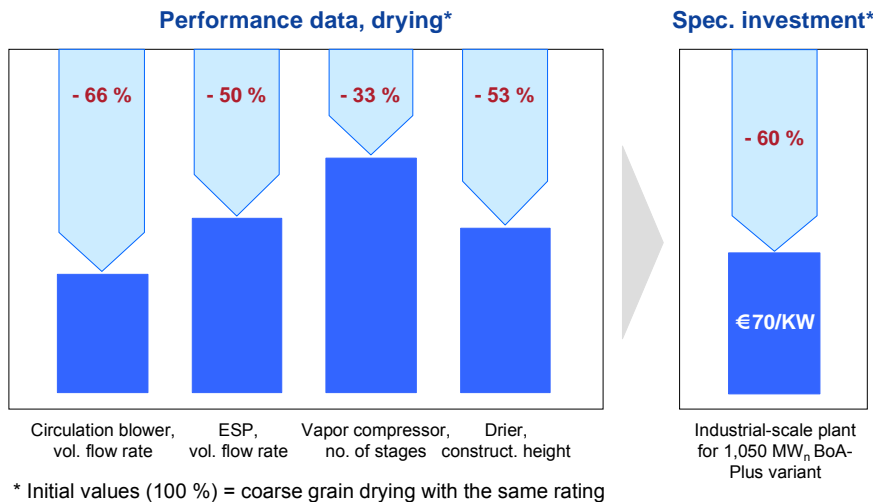
WTA fine grain drying permits significant improvements in spec. capacity and reduction in investment costs.

Figure 17: The Breakthrough in Terms of Capacity, Technology and Costs by WTA Fine Grain Drying

What is more, the fine grain size of coal causes a rise of approx. 80% in the heat transfer efficiency. The potentials of fine grain drying were fully confirmed by the operating results obtained in the WTA test plant.

Pilot-scale drier, Niederaussem

Ø 14,500
□ 9,000
10,411
2,700
4,200
4,150
18.8 m

WTA fine grain drier
of the same capacity

□ 7,000
4,000
2,700
1,847
300
8.9 m
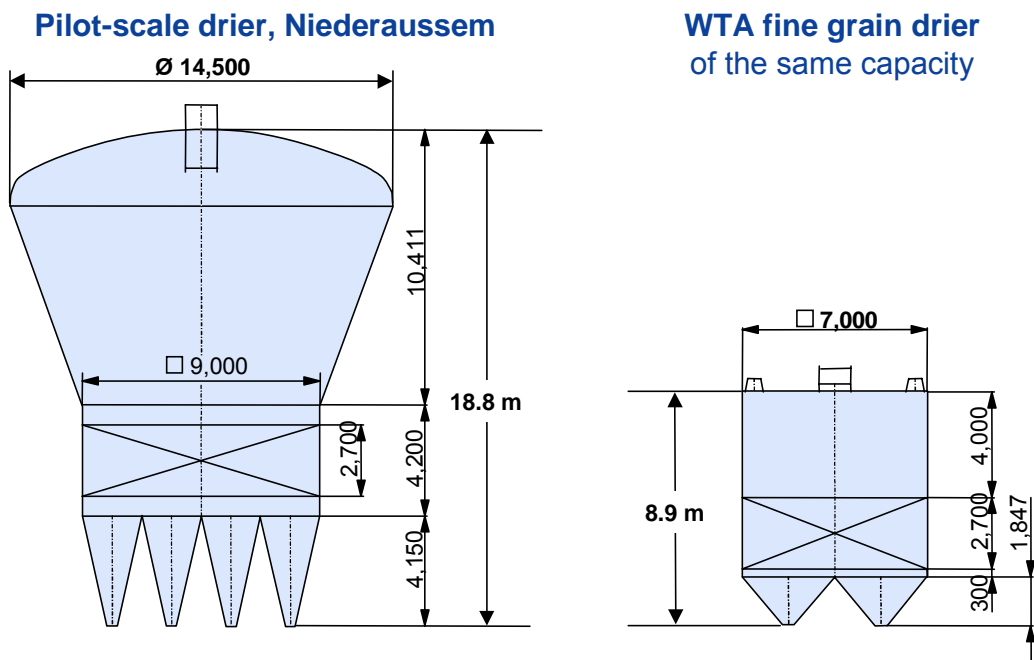
Drier volume reduced by almost 70 %.

Figure 18: The Breakthrough in Drier Technology

Compared with coarse grain drying used so far, these positive results and the findings from accompanying theoretical work entailed a marked reduction in the equipment-specific outlays on the core components of WTA fine grain drying. The size of the core components, viz. drier, electrostatic precipitator (ESP), fluidization blower, is almost

halved and the vapour compressor is reduced by one third in size. Supplementary optimisation work on the total equipment allowed the specific investment costs to be cut by 60% as against those arising for WTA coarse grain drying.

4.2.4. Industrial-Scale Plant Concept for WTA Fine Grain Drying

Based of the fine grain milling and WTA fine grain drying techniques, the industrial-scale plant concept for the pre-drying system of a 1,050 MW$_{net}$ BoA-Plus power plant was developed. Figure 19 shows the block diagram for the pre-drying system. It has a per hour raw coal throughput of 890 tonnes or a dry coal output of 460 tonnes per hour.
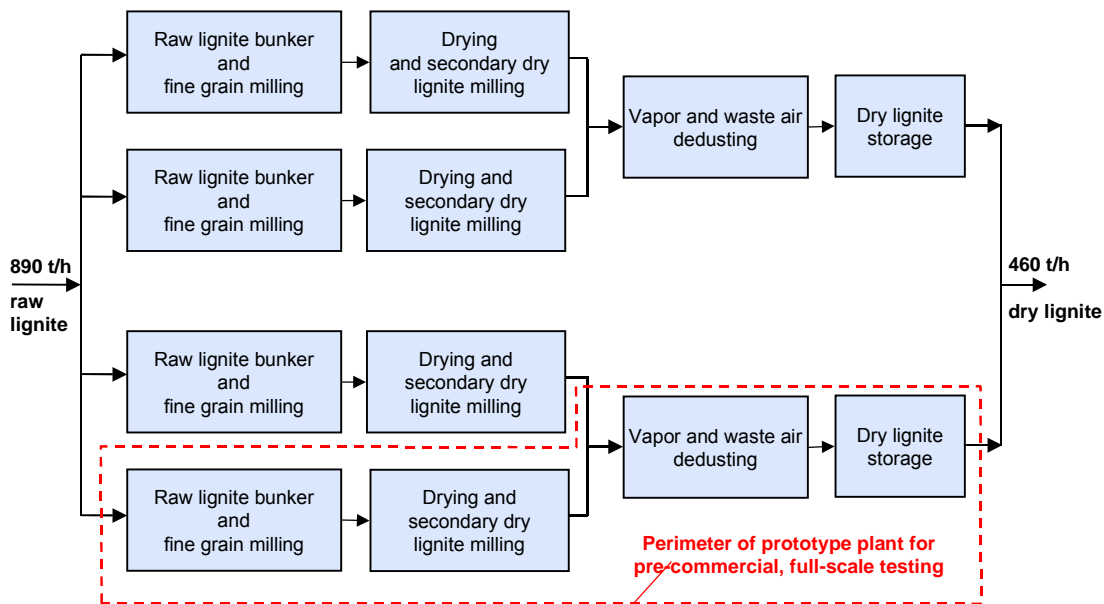
Figure 19: WTA Fine Grain Drying for BoA-Plus, Hambach lignite, power plant capacity 1,050 MWnet

There are four solids material lines, and two gas cleaning lines. The concept includes secondary dry coal milling which allows a grain size of 0 – 1 mm to be reliably achieved. Only 1% is greater then 1mm and 60% greater then 90 µm. So the PF is clearly finer than that of today's raw lignite-fired boilers. In the average the grain size of the installed milling systems changes between 4% and 9% above 1 mm. It depends on the mill type performed with or without preheateror without classifier and on the condition of the wear parts.

The pre-drying system, incl. raw coal bunker, fine grain milling and WTA fine grain drying, is combined in a compact arrangement and installed immediately beside the steam generator of the BoA-Plus power plant.

The investment costs of the entire pre-drying system are around € 70/kW. To demonstrate commercial-scale application, it is planned to erect and test one full-scale line of this BoA-Plus pre-drying system as a prototype at the BoA unit.

4.2.5. Dry Lignite-Based Boiler Technology for BoA-Plus

If we compare existing steam generators, having conventional raw lignite firing systems, with the new dry coal-fired systems

The following design criteria are to be observed:

1. The furnace gas exit temperatures are only dependent on the ash properties and not on any possible fuel pre-drying. Dry lignite-fired steam generators are therefore designed with similar furnace gas exit temperatures to those of steam generators fired with raw lignite. Due to the higher adiabatic combustion temperature, more heat is transferred in the combustion chamber result which has a considerable effect on the furnace design.

2. With the new firing concept, the combustion chamber is symmetrically fed with fuel. Non-symmetries, as are inevitable for raw lignite-based firing systems, are avoided. In addition to uniform fuel supply, an optimum temperature profile is obtained with hot zones in the center of the furnace cross section and colder zones at the edge.
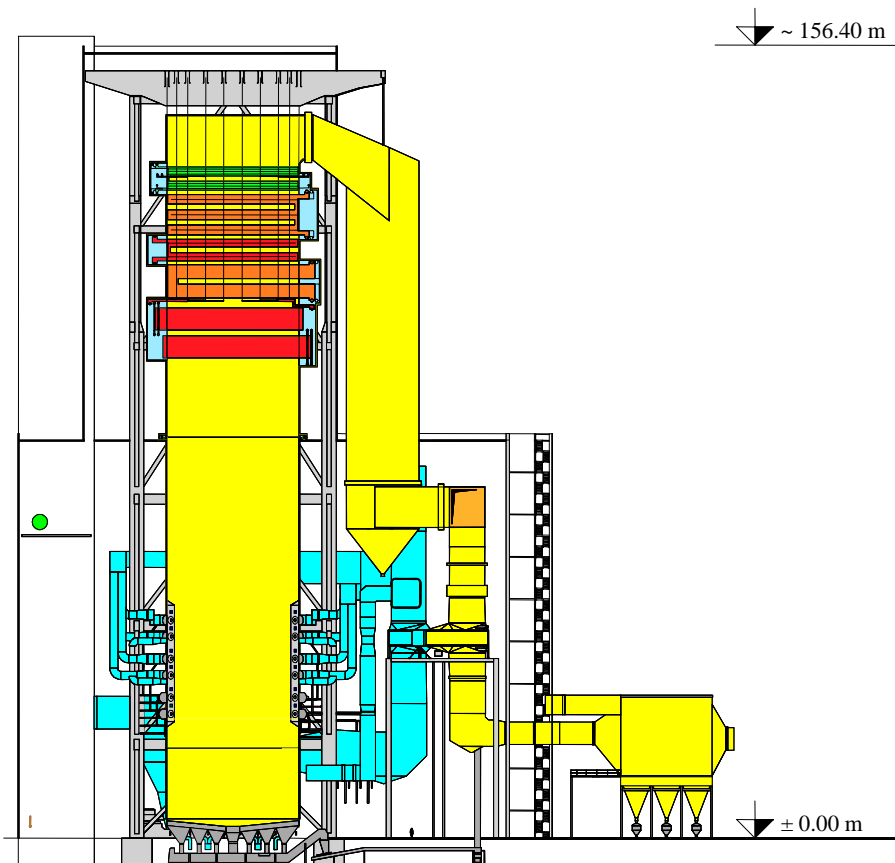
Figure 20: BoA-Plus Steam Generator of the 1,000 MW class

Consequently, the furnace gas exit temperature is approx 20K higher than that of comparable raw lignite-fired versions. This slight increase combined with the symmetric furnace configuration results in the lower temperatures at the entry to the economizers and air heaters.

With these criteria, a combustion chamber for a 1,050 MW plant can have un-economical dimensions with currently available wall materials when firing coal with higher heating values. Adhering to existing design principles would lead to a furnace with height of more than 100m. In order to return to economically efficient dimensions, a flue gas recirculation system - the installation of a flue gas recirculation system has to be avoided, if possible - can be used. Also, an attempt has to be made to reduce the vertical furnace dimension and thus the construction height by using a more generous furnace cross section. Nowadays, cross sections of 26 by 26m are considered controllable. Furthermore, this leads to a more moderate cross-sectional area heat release which in turn lowers the temperature level in the principal combustion zone.

As already mentioned, the symmetrical firing concept the main difference between the pre dried lignite fired and the raw lignite-fired steam generator. This criterion also guarantees uniform feedstock supply of the furnace during partial-load operation. Temperature mal-distribution as encountered in raw lignite-fired plants due to non-symmetrical mill configuration and therefore non symmetrical furnace operation can be avoided. This configuration allows more uniform heat flux and temperature distributions in the burner area which will reduce slagging. This has been corroborated by the modeling (Ref 7). Similar to the hard coal-based tangential firing system, the burners are arranged in the corners, which maximizes the use of the furnace volume. Furthermore, this arrangement minimizes the back-flow zones at the individual burners. As a result, smaller amounts of hot flue gases containing unburned coal particles reach the combustion chamber wall, which would cause in the other case fouling of the chamber wall. The pronounced radial temperature profile is produced by directing part of the secondary air more towards the walls accumulating in this way more combustion air in the wall area. Owing to the larger air supplies, this leads to lower temperatures in the peripheral area which reduces the propensity for fouling.
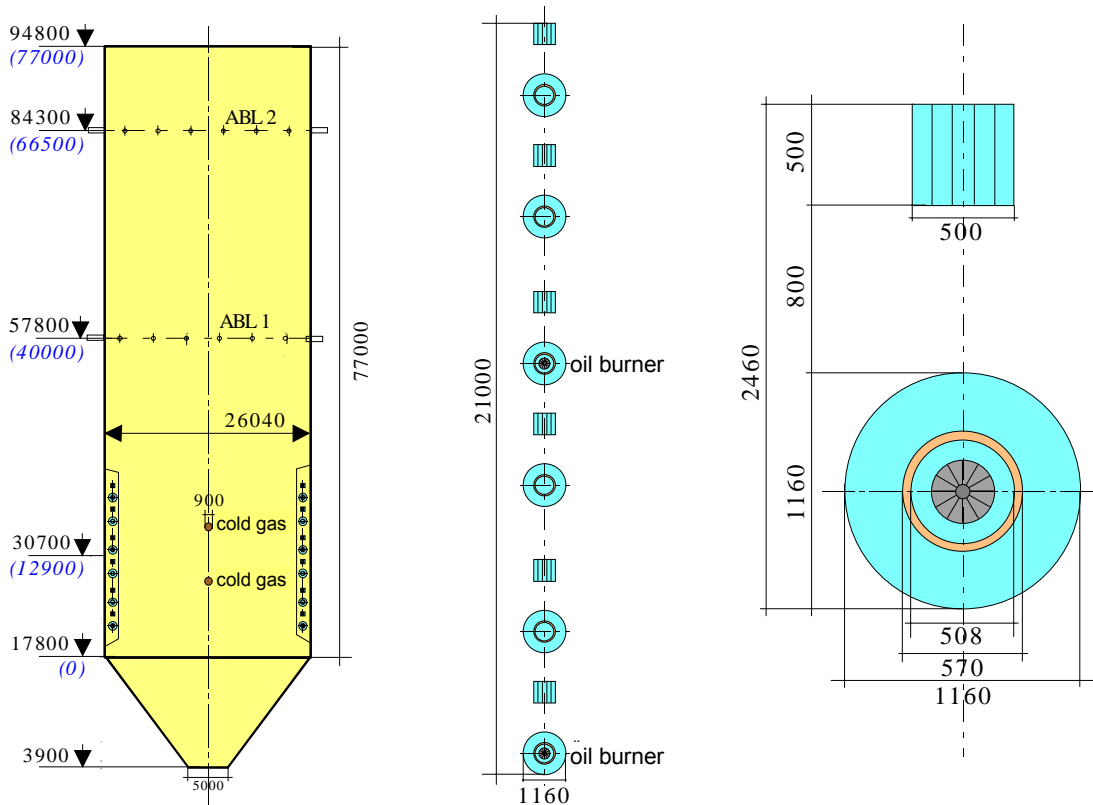
Figure 21: Firing Concept for an Industrial-Scale, Dry Lignite-Fired Boiler

The figure gives an overview of the firing concept. It includes a combustion chamber for a 1,050 MW steam generator. The burner array of a combustion chamber corner consists of six dry lignite-fired burners arranged one on top of the other. Each of these burners has been allocated a wall air opening. The oil pilot burners are integrated in the dry lignite-fired burners. These pilot burners are used with dry pulverised lignite, as well as for hard coal-based firing systems. These fuel oil burners centered within the dry lignite burner and equipped with a swirl are used for ignition firing.

This firing configuration with radial staged air supply represents the state of the art for modern hard coal-based firing systems. In addition to this type of air supply, two burnout air levels are planned. With this staged air supply concept, compliance with the statutory emission values for NO$_x$ and CO is guaranteed. It is possible to demonstrate that the measurement results obtained from dry lignite-fired test plants fall below these values. In pulverized lignite-fired plants of lower capacities, the limits were almost always achieved. Furthermore, co-combustion tests with dry lignite in conventionally fired plants showed that this operating mode did not cause any rise in NO$_x$ emissions. In industrial-scale plants with long residence times and efficient staged air supply, the statutory emission limit values are therefore reliably achieved.

The combustion chamber will be equipped with state-of-the-art tube cleaning devices. They include a combination of water-lance and water-jet blowers. The latter are used in the principal burner area since experience obtained from industrial-scale plants has shown that water-jet blowers are more effective there. The arrangement of the burners in the corners improves the cleaning possibilities in the burner belt area.

For testing dry lignite combustion, constructing the pre-drying prototype at a BoA unit and using will yield valuable results that will underpin the design of the dry lignite-based firing concept.

4.2.6. BoA-Plus Economics

To assess the costs and the efficiency potential of a BoA-Plus power plant unit compared to a BoA power plant unit, RWE Rheinbraun, together with ALSTOM Power, conducted a detailed study.
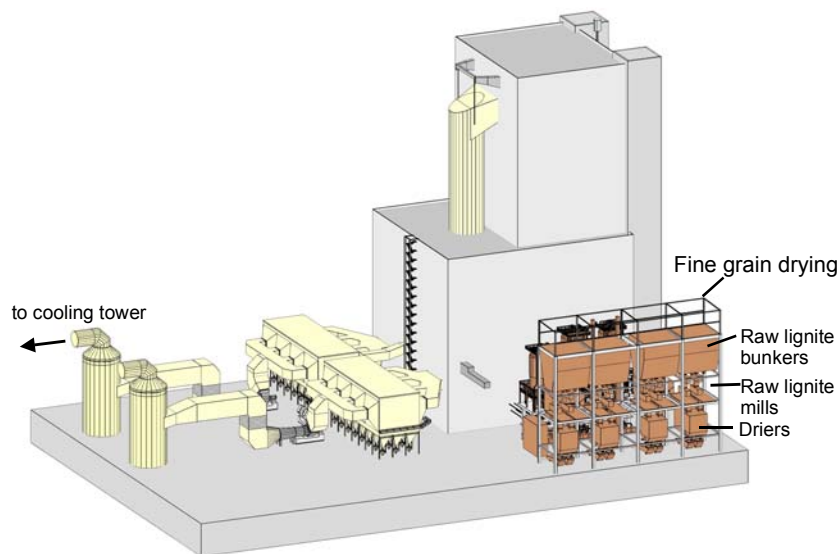
Figure 22: BoA-Plus with WTA Fine Grain Drying

The reference in each case was a power plant unit with an electrical net output of 1,050 MW, having a comparable thermodynamic and process engineering design, as well as the same condition for plant machinery and equipment. The design-related results for the pre-drying system and steam generator were already discussed in the previous section. Compared to the BoA unit, the BoA-Plus unit is more efficient by 4 to 6 percentage points, dependent on the feed coal quality (heating value, moisture and ash contents).

In the cost comparison, the key differences are the additional costs of approx. € 70/kW arising from the upstream drying system, including building and offsites, and a modified overall design. This, however, should be compared to savings of about the same magnitude in the BoA-Plus power plant itself. Savings of approx. € 52/kW can be achieved in the steam generator. These savings are primarily due to the fact that the raw coal bunkers, the eight raw coal mills and the flue gas recirculation shafts can be dispensed with. Another € 15/kW results from a multitude of single effects, e.g., from the dimensions of the entire flue gas path, including flue gas cleaning, which are smaller because of the missing coal moisture, an optimally adapted steam process and reductions in common plants since the entire raw coal infrastructure is no longer required. On balance, the investment costs of BoA-Plus and BoA are more or less the same. Therefore, the pre-drying system allows the efficiency to be increased without any additional investment cost. So for the power generating costs, the BoA-Plus concept has some advantages over the BoA plant.
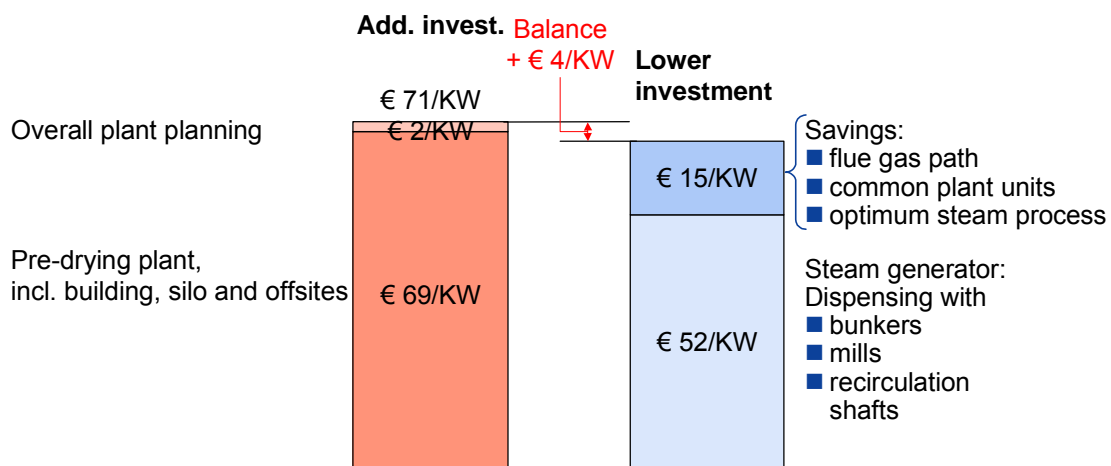
Almost the same spec. investment costs attained thanks to very favorably-priced pre-drying system

Figure 23: Investment Costs of BoA-Plus versus BoA, Power plant capacity 1,050 MW $_{net}$

The crucial breakthrough in improving the economics for the future BoA-Plus version has been attained by the fine grain drying technique. Compared with the development status of 1997, the higher efficiency due to improved heat and process engineering and the structural simplicity allowed the investment costs of pre-drying to be reduced from around € 100/kW to € 70/kW.

4.2.7. BoA-Plus Commercialisation

RWE Rheinbraun has decided to bring to commercialization the pre-drying variant for BoA-Plus based on the WTA fine grain drying.

In a first step to achieve this goal, the tests in the WTA fine grain drying plant at Frechen are being intensified this year. Based on the results obtained, a prototype plant for WTA fine grain drying is planned to be constructed and tested, together with the dry coal firing system in the BoA plant unit as from 2004 in a second step.

The scaled up WTA plant fine grain drying plant at the BoA 1 unit is under construction. For demonstration and further development of the technology the WTA unit shall

supply about 25% of the fuel as predried fuel to the plant. Commissioning is scheduled for December 2007. First results and figures about the operational performance are expected by mid 2008.
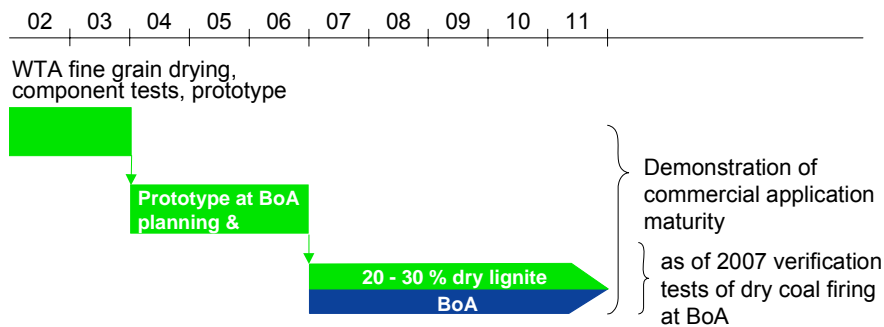
Planned investment costs, prototype plant: € 30 mill.

Target: Full operativeness for construction planning as from 2008.

Figure 24: The Way to Commercial Application Maturity for WTA Fine Grain Drying

This prototype version corresponds to one line of the future, commercial-scale BoA-Plus pre-drying system with a total of four lines (Figure 6). The planned raw coal input of approx 220 tonnes per hour permits the production of some 25 to 30% of the furnace capacity of the BoA unit by means of dry coal burners. In this way, sufficient dry lignite combustion experience can be obtained. For the prototype project, a capital expenditure budget of €30m has been provided.

The tests of the prototype plant are aimed at demonstrating the commercial suitability of pre-drying until the start of the planning work on the third BoA unit.

4.2.8. Further Efficiency Developments in Lignite-Based Power Plant Technology

In parallel with the pre-drying technique development in the lignite industry, comprehensive developments are under way in the field of coal-based power plant technology to increase efficiency by increasing steam parameters from max. 600°C and 275 bar for main steam and 610°C for reheat steam to main steam conditions of more than 700°C and 375 bar. There are two programmes the EU project "AD 700" and VGB's power plant initiative "E-Max". However, it will not be before 2010 that the industrial-scale demonstration of key components for this power plant technology, have been evaluated so the planning of a 700°C lignite-fired power plant on a 1,000 MW scale design will not be available until after then, about 2020. Because of the higher material costs, current estimates suggest that such a power plant will have about 10% higher investment costs than those for today. Figure 25 shows the timings of the expected efficiency increases.

Based on current knowledge, it seems feasible that the 50% efficiency threshold will be surpassed by a 700 °C lignite-fired power plant with integrated pre-drying in about 2020. This shows that the implementation of the improvement potential will be a medium- to long-term process.

Net efficiencies
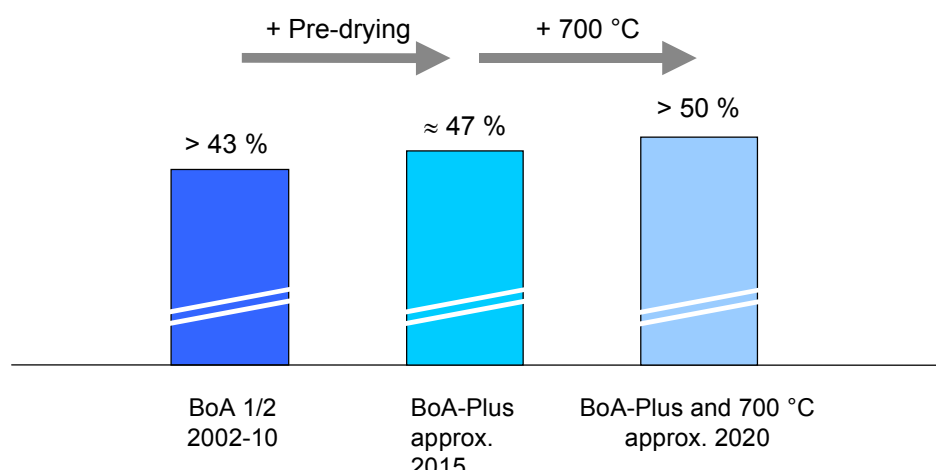
Noticeable efficiency increases after 2015 are commercially feasible.

Figure 25: Efficiency Potential for Lignite-Fired Steam Power Plants

With the pre-drying process, lignite-derived power generation has an additional factor leading to efficiency increases compared with hard coal-based power generation. Due to this process, the lignite-based power plant technology will no longer be at an efficiency disadvantage compared to hard coal.

4.3. Impact of Greek Lignites on BOA Plant Design and Performance

The development of the milling and firing system installed in the BoA Power plant in Germany depended on the coal quality of the open cast mine, which has changed due to the special conditions of the deposit.

The lignite coal of Florina mine includes xylite elements, which may cause problems in the milling and firing system.

The fuel specification parameters that affect boiler design and performance are the ash and water content and the net calorific value.

4.3.1. Comparisation of Lignites

Item	Units	Rhenish	Drama	Ptolemäis	Florina
Water content	%	53,0	57,8	51,1	37,4
Ash content	%	5,0	16,1	17,3	27,2
NCV	MJ/kg	8,700	4,380	5,360	7,890

As shown in the table above there are significant differences.

Water content is decreasing from the Rhenish coal to the Florina coal, but ash content is increasing, so that the net calorific value of Drama and Ptolemäis coal is very low. There is an impact on the milling system, the firing system and the boiler construction.

4.3.2. Drying Heat related to NCV

Item	Units	Rhenish	Drama	Ptolemäis	Florina
Water content	%	53,0	57,8	51,1	37,4
NCV	MJ/kg	8,700	4,380	5,360	7,890
Drying Heat related to NCV	%	14,9	32,2	23,2	11,6

In the table above an "index value" is produced based on the water content and the NCV of the coal, this number describes the requirement the coal places on the drying system.

The relative value of Drama coal is highest and indicates that about 30% of the heating value is to be used for drying the coal. It is twice as high as the value of a Rhenish coal. This results in special conditions for the lay out of the milling-, drying - and the burner system.

The value of Ptolemäis coal is reduced and approaching the value of Rhenish coal. It also requires an optimisation of the respective systems.

The value of Florina is comparable to the value of Rhenish coal and there should be no problem for the drying process, but unlike the rhenish coal there exists a bigger part of xylite elements within the Florina coal. This may cause problems in the milling system in achieving the required grinding fineness and problems in the furnace because xylite particles need a long burn out time.

4.3.3. Flue Gas Mass related to NCV

Item	Unit	Rhenish	Drama	Ptolemäis	Florina
Water content	%	53,0	57,8	51,1	37,4
NCV	MJ/kg	8,700	4,380	5,360	7,890
Flue gas Related To NCV	kg /MJ	0,54	0,69	0,62	0,51

In the table above another index value is formed from the NCV of the coal analysis and the mass flow of flue gas operating with excess air of 10%.

A comparison of the index Values demonstrates that the highest amount of flue gas related to the applied heat is associated with the Drama coal followed by Ptolemais coal. The value of Florina coal is similar to the Rhenish coal.

The increase of the specific flue gas mass flow results in a larger absolute mass flow of flue gas in the boiler for the same fuel heat consumption. Therefore the dimensions of the boiler have to be increased and the heat transfer between the flue gas and boiler surfaces has to be modified.
The higher volume of flue gas has an influence on the firing system and the flue gas temperature furnace exit.

A stable flame is achieved by the burner design and the boiler tube heating surface must be increased in order to absorb the heat of the flue gas and decrease the waste gas temperature.

Concerning the burner design the higher flue gas mass flow of the greek lignite causes a different layout to ensure a adequate flame development and behaviour in order to achieve stable firing and sufficient NOx reduction. This behaviour depends on the flue gas and air velocity leaving the burner and the coal - flue gas ratio importing the firing heat to the burner mouth. The relation between this items is very important for the ignition and burning of the lignite. Thus using coal with high flue gas ratio amongst others the burner areas must be increased to assure equal velocities.

This will result in an increase of the electrical power demand of the Induced Draft Fans, so that the net boiler efficiency will decrease.

The capital cost will also increase due to the enlargement of the firing system, the heating surfaces and the boiler dimensions.

4.3.4. Specific Coal Mass related to NCV

Item	Unit	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Coal mass Related To NCV	kg/MJ	0,115	0,228	0,186	0,127

The table above shows the demand of coal mass flow depending on the NCV.

It is evident that the largest specific fuel mass flow is produced by the Drama coal, nearly twice as much as the Rhenish coal. This affects directly the milling system with the mill itself and the total coal handling plant, increasing the dimensions and so the capital cost.

The power consumption of the drive motors will also increase with the result of reduction in the net efficiency of the power plant.

In a similar way the ash content is to be compared related to the NCV in the following table.

4.3.5. Ash Content related to NCV

Item	Unit	Rhenish	Drama	Ptolemäis	Florina
Ash content	%	5,0	16,1	17,3	27,2
NCV	MJ/kg	8,700	4,380	5,360	7,890
Ash mass Related To NCV	g/MJ	5,74	36,8	32,2	34,5

The high ash mass flow values for all three Greek lignites indicate an increase in the ash handling plant three times larger then for the rhenish coal.

The high ash value also causes an increase of the unburned coal in the wet ash of the furnace bottom and the dry ash of the precipitator system. Heat dissipation also occurs by the increased mass flow of discharged ash.

A decrease of boiler efficiency and an increase of auxiliary power consumption results from the higher ash volume. increases capital cost and reduces the net efficiency.

4.3.6. Sulphur content related to NCV

Item	Units	Rhenish	Drama	Ptolemäis	Florina
Sulphur content	%	0,4	1,0	0,4	0,7
NCV	MJ/kg	8,700	4,380	5,360	7,890
Sulphur Mass Related To NCV	g/MJ	0,482	2,264	0,765	0,897

A detailed description of sulphur contents comparison and operational behaviour is given in section 6.

4.3.7. Flue Gas Losses

Item	Units	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Excess air		1,10	1,10	1,10	1,10
yO2 dry	%	1,9	1,9	1,9	1,9
xH2O wet	%	15,4	23,4	19,8	14,2
Waste Gas Temperature	°C	120	120	120	120
Waste Gas Losses	%	5,8	7,9	6,9	5,5

The table compares the flue gas losses to be expected for the different lignites based on the combustion calculation using the parameters of the different lignites. Due to the moisture and ash content of the Greek lignites the waste gas losses increase.

4.3.8. Boiler Efficiency

Item	Units	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Waste Gas Losses	%	5,8	7,9	6,9	5,5
Losses: Ash heat and unburned	%	0,70	4,57	4,00	4,29
Radiation Loss	%	0,5	0,5	0,5	0,5
Total Losses	%	7,0	13,0	11,4	10,3
Boiler efficiency	%	93,0	87,0	88,6	89,7

The boiler efficiency for the different lignites is produced based on the losses.

The high ash contents leads for the Greek lignite to higher losses. The calculations are bases for all lignites with the same value of 4% unburned carbon content in the ash.

4.3.9. Turbine Heat Consumption

Item	Units	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Turbine Heat Consumption	kJ/kWh	7347	7500	7500	7500
Turbine Heat Consumption	%	49,0	48,0	48,0	48,0

The turbine heat consumption is affected by the turbine efficiency, the boiler water and substantially by the condenser steam pressure. This pressure depends on the design of the cooling system and the yearly average ambient temperature, which is much higher in Greece than in Western Germany.

4.3.10. Auxiliary Power Consumption

Item	Units	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Auxiliary Power Consumption	%	5,0	6,0	6,0	6,0

As already mentioned above the lower net calorific value combined with higher ash and water content affects the design and the auxiliary power consumption of the following components:

- coal ash handling
- milling system
- flue gas conveyance
- FGD spraying water transport

An estimation of the auxiliary power consumption values is shown in the table above.

4.3.11. Unit Net Efficiency

Item	Units	Rhenish	Drama	Ptolemäis	Florina
NCV	MJ/kg	8,700	4,380	5,360	7,890
Turbine Heat Consumption	%	49,0	48,0	48,0	48,0
Boiler efficiency	%	93,0	87,0	88,6	89,7
Auxiliary Power Consumption	%	5,0	6,0	6,0	6,0
Unit Net Efficiency	%	43,3	39,3	40,0	40,5

The summary of all items affecting the unit net efficiency is presented in the table above. The impact of the different coal qualities, affect the values of net efficiency. Lowest values are produced by the coal qualities of Drama and Ptolemais and it has to be mentioned, that this coal quality is already at or beyond the limit of application of BoA Technology and would require the boiler manufacturer has to model and modify the firing system.

The coal quality of Florina is similar to the Rhenish but with a much higher ash content and so has a lower boiler efficiency. In all case the ambient temperature difference affects the net efficiency of the Turbine.

4.3.12. Investment costs

		Rhenish coal	Greece coal (Drama and Ptolemäis)
Gross Power Generation	MW	1100	1100
Capital	€/kW	1100	
Boiler plant capital: (Coal Feeder, Milling system Flue gas, Precips, FGD etc)	%	40	40
Increase flue gas mass flow	%	0	30
Increase capital of boiler plant	%	0	17
Increase total capital	%	0	7
Capital	€/kW	1100	1177
Reducing the unit size to	MW	600	600
Increase of specific capital to	€/kW	1359	1455

The influence on capital cost is shown in the table above. The capital depends critically on the seize of power plant. Therefore, the unit size of BoA has grown to 1100 MW gross. Due to the difficulty of calculating the capital exactly the validated costs of BoA Plant have been used.

The main impact of coal quality concerns the boiler and flue gas plant with FGD and Precipitator. The increase of the flue gas mass flow of 30% increases the capital cost of the boiler by 17%.To calculate the increase of investment due to the higher flue gas mass flow the following assumption is made: There is no linear effect from the flue gas mass flow of the boiler to the investment but an exponential effect with an exponent of 0,6. Thus the increase is calculated to + 30% = 1.30; ($1.30^{0.6} = 1.17$); 1.17 = +17%. This results in an increase in the total capital of 7%. The specific capital cost increases from 1100 €/kW to 1177 €/kW.

Depending on the grid and the operation mode, the size of the unit may be only 600MW. The specific value of the capital will increase due to the non-linear scaling cost with unit size. The specific capital cost is 1359 €/kW for the Rhenish coal and 1455 €/kW for the Greek coal. The further investigation of the Greek coals: Drama and Ptolemäis must be performed before applying BoA Technology.

4.3.13. Summary : Application of BoA Technology to Greek Coal
The BoA Technology comprises the application of new technology to all parts of the power plant. In particular the boiler is built for higher steam pressure and temperature

and waste heat in the flue gas is utilized to preheat the boiler feedwater.

Many problems due to coal quality have been solved to achieve the efficiency, availability and environmental capability of the BoA Plant.

Further technical investigations are necessary to apply the BOA plant concept boiler design to the Greek lignite, especially with the coals from Drama and Ptolemäis, which are quite different to the Rhenish lignite. The remaining parts of the plant may be similar to the BoA Technology.

These issues may be mitigated by using the developing BoA Plus Technology: BoA Plus Power Plant is fired with lignite, which has been pre-dried in a separate WTA drying plant.

Currently RWE is building a full scale WTA drying plant at the BoA Plant in Niederaußem, where 20-30% lignite will be co-fired for two years, before RWEI build the first commercial BoA Plus Plant in 2012 to 2015.

4.3.14. Research into the drying of Greek Lignite for BoA Plus Technology

Currently, PPC and RWE are participating in the EU-sponsored research programme "Commercial-Scale Testing of a Fluidized-Bed Drying Plant for highly Efficient Lignite-Fired Power Plants (DRYCOAL)". As part of the programme, it is planned to

- determine the drying characteristic of a sample of lignite from Greece at RWE Power's laboratory test facility, and
- carry out co-firing tests of dry lignite with raw lignite at Liptol power station in Greece, to determine the firing characteristics of the dried lignite.

If the results of these tests are positive, it is planned to investigate the suitability of the WTA drying technique for Greek lignite in more detail at RWE Power's WTA-2 plant in Germany and to investigate the feasibility of a power plant based on pre-dried Greek lignite.

5. Gas Turbine Re-powering at Weisweiler Power Station Topping gas turbine Plant G and H

Figure 26:

Tasks and Goals

RWE Power AG is planning to extend the two existing 600 MW lignite blocks with one topping gas turbine plant each at the Weisweiler site.

With this concept, the lignite blocks can continue to be included in base load generation and the topping gas turbines can be connected at short notice according to the power supply network requirements to provide MW flexibility.

It is therefore possible to meet the increasing demand for back-up electricity (grid control) from the increased use of wind energy.

By connecting the gas turbine plants with the lignite blocks, their waste heat is used in the systems of the lignite blocks as a combined heat and power generation process and therefore leads to an improvement in the overall efficiency of the plant.

5.1. Project history

After an initial concept assessment phase, which began in April 2003, and subsequent competition for the turnkey delivery and installation of the topping gas turbine plant, a contract with Lurgi Lentes AG, Düsseldorf was signed in June 2004.

Immediately after conclusion of the contract signing, work began on preparing for

approval the application required by the Federal Emission Protection Act. The approval was applied for at the end of August 2004 from the local government authorities in Cologne and was granted by them on the 2nd of February 2005.

After performing various preparatory works on the building site, the erection of the plant began in March 2005. Completion and commencement of commercial operation of the two plants is planned for July (Block G) and December 2006 (Bock H) respectively.

The total investment volume for the Weisweiler topping gas turbine project is €150m.

Table 1.

	2003	2004	2005	2006
Concept phase / competition				
Approval phase				
Submission of application for approval		27.08.		
Granting of approval			02.02.	
Erection phase				
Sanitation of existing stack				
Earthwork, erection of building				
Component installation				
Commissioning, trial operation	2003	2004	2005	2006
1st firing of gas turbine block G				28.03.
Completion, commencement of commercial operation block G				10.07.
1st firing of gas turbine block H				04.09.
Completion, commencement of commercial operation block H				18.12.

5.2. Location

The Weisweiler power station is located east of Aachen and north of the Weisweiler district of the city of Eschweiler on the A4 motorway.

The site has two blocks each of power classes 150, 300 and 600 MW which are fuelled by lignite from the adjacent open cast mine of Inden and used in basic load operation.

In addition to lignite, paper sludge is also burned as a substitute fuel in the boilers of blocks G and H, contributing to an environmentally friendly disposal route for this residual material.

In addition to generating electricity in the base-load range, the Weisweiler power station also provides district heating for the city of Aachen, the Eschweiler industrial and commercial estate and the Jülich Research Centre.

5.3. Plant Concept

The term "topping gas turbine plant" (TGT) means that the new plant is only operable in conjunction with the respective lignite block and

- Uses existing systems which saves on investment costs
- Uses the planned reserve capacity of the blocks and therefore improves the overall economics.

One gas turbine using natural gas having an electrical power output of approx. 190 MW is installed per lignite block.

The gas turbine exhaust temperature is 580°C. This waste heat is transferred in water pre-heaters in the lignite block boiler feedwater system.

Consequently the use of steam from the steam turbines there can largely be dispensed with resulting in and an increase in power from 640 MW to 720 MW.

The flue gases of the gas turbine are cooled down to approx. 95°C and are discharged to atmosphere via the stack in block H which has not been used since retrofitting the lignite blocks with flue gas desulphurisation plants.
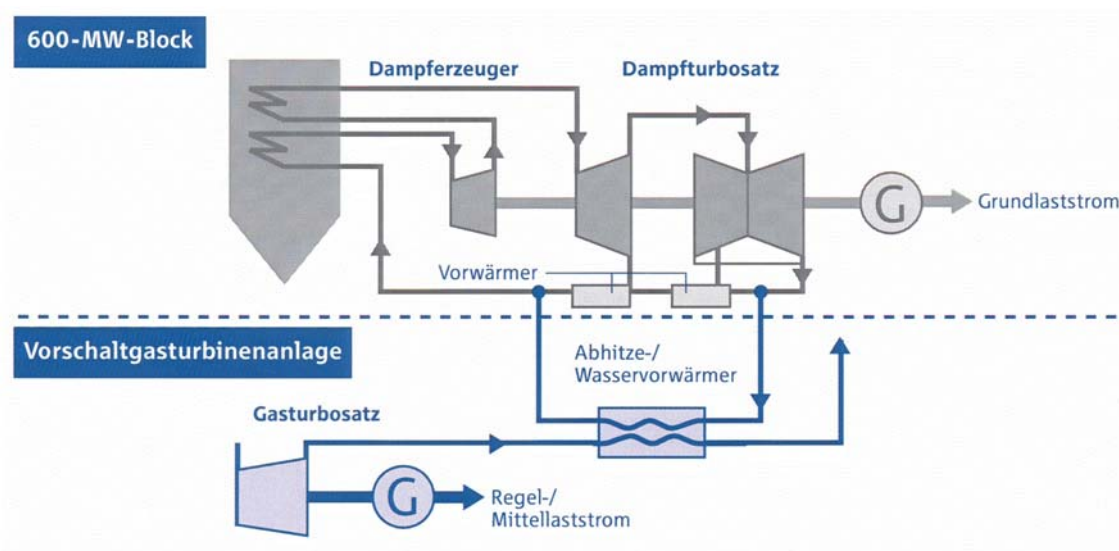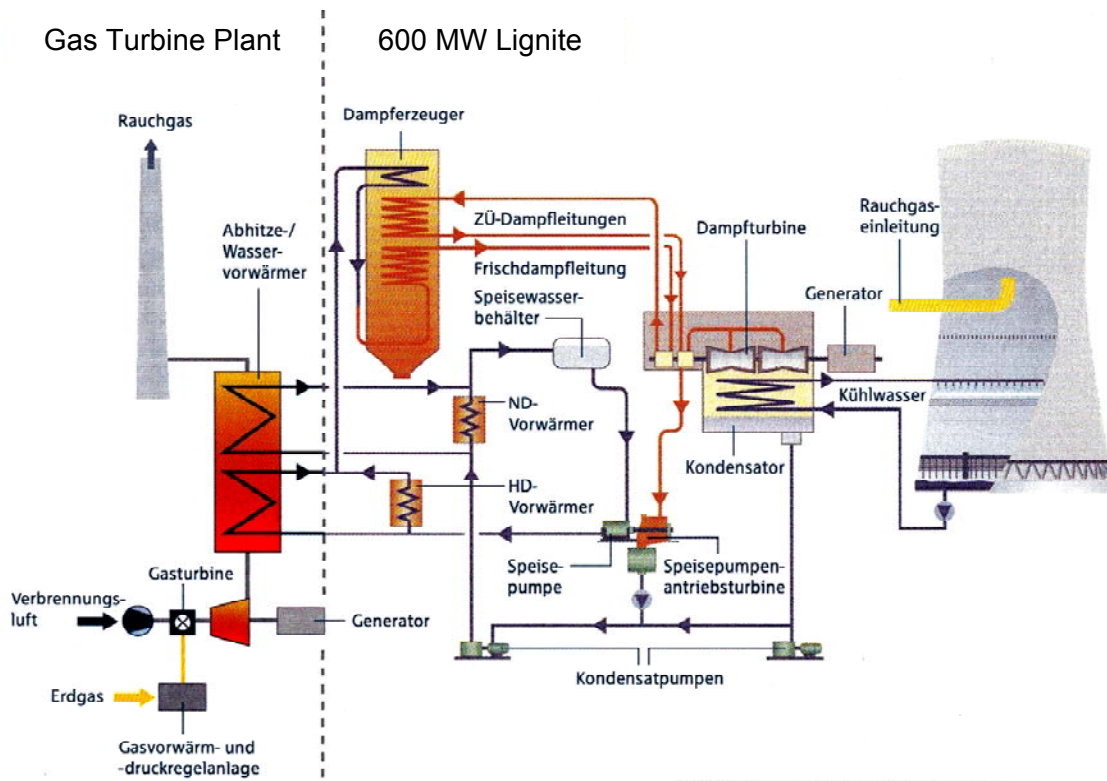

Figure 27:

| Gas Turbine Plant | 600 MW Lignite |

Figure 28:

Process flow diagram

Vorschaltgasturbinenanlage	=	topping gas turbine plant
600-MW-Braunkohlenblock	=	600 MW lignite block
Rauchgas	=	flue gas
Abhitze-/Wasservorwärmer	=	waste heat/water pre-heater
Gasturbine	=	gas turbine
Verbrennungsluft	=	combustion air
Erdgas	=	natural gas
Gasvorwärm- und –druckregelanlage =		gas pre-heating and pressure regulating system
Dampferzeuger	=	steam generator
ZÜ-Dampfleitungen	=	intermediate overheater steam pipes
Frischdampfleitung	=	fresh steam pipe
Speisewasserbehälter	=	feedwater tank
ND-Vorwärmer	=	LP pre-heater
HD-Vorwärmer	=	HP pre-heater
Speisepumpe	=	feed pump
Dampfturbine	=	steam turbine
Kondensator	=	condenser
Speisepumpenantriebsturbine	=	feed pump drive turbine
Kondensatorpumpen	=	condenser pumps
Generator	=	generator
Kühlwasser	=	cooling water
Rauchgaseinleitung	=	flue gas pipe

5.4. Plant Structure and Function

The plant comprises the following components:

5.4.1. Natural Gas Pressure Reduction Station

The natural gas is supplied from a natural gas pipeline via a new connection pipe. The pressure in this system may be up to 90 bar for operation reasons so that the gas has to be reduced to about 30 bar before being used in the gas turbine. Since the temperature of the gas falls drastically in the pressure reduction, it has to be heated for use in the gas turbine.

5.4.2. Gas Turbo Sets

Each of the two lignite blocks is preceded by a gas turbine set consisting of compressor, gas turbine and generator.

The compressor draws in the combustion air through an air filter system and compresses it to a pressure of approx. 17 bar. The compressed air enters the combustion chamber of the gas turbine where natural gas is supplied and burned by 24 burners distributed around the circumference. The combustion produces flue gas at approx. 1,100°C for entry.

5.4.3. Waste Heat/Water Pre-Heaters

The waste heat from the flue gas leaves the gas turbine at approx. 580°C and is used in the water pre-heater. Condensate and feedwater is fed from the lignite block to the heat exchanger through pipes, heated up and integrated in the feed heating system of the lignite block again.

5.4.4. Stack

After leaving the water pre-heater the flue gases at approx. 95°C are fed through separate flue gas ducts to the existing stack in block H. The stack which has not been used since retrofitting the lignite power stations with flue gas desulphurisation plants will be shortened from 180 m to 160 m and renovated before being re-used.

5.5. Energy Discharge

The generator runs at 15.75 kV, and this is transformed into 110 kV in the machine transformers to allow it to be transported with low transmission losses. The works power requirements of the topping gas turbines is drawn from the transition of the generators to the machine transformer and transformed to 6 kV or further to 400 V.

5.6. Layout, Main Buildings

The topping gas turbine plant is being built to the north-east of the lignite block H in a free area providing short access routes for the condensate and feedwater pipes to the lignite blocks and to the stack H for flue gas discharge. The plant will include the following main buildings:
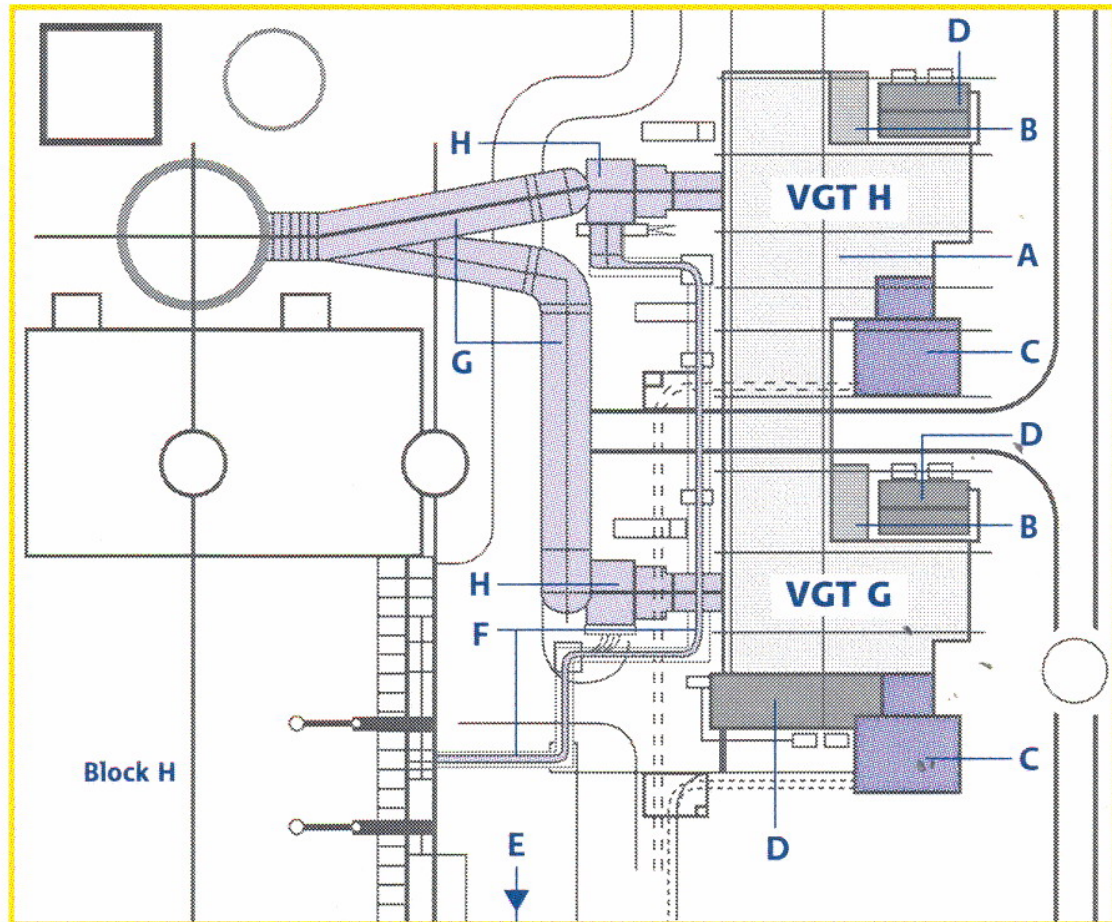
Figure 29:

5.6.1. A, Gas Turbine Building

As a central building wing for accommodating the two gas turbines, consisting of gas turbine and generator

5.6.2. B, Lubricating Oil Supply

For every gas turbine in separate building wings adjacent to the gas turbine building

5.6.3. C, Energy Discharge

Comprising the fire protection walls and the oil collection troughs of the machine and transformers, respectively, south of the generator bays of the machine house

5.6.4. D, Switchgear Building

Built adjacent to the south wall of the gas turbine building for accommodating the switchgear and the process control technology of the whole plant as well as the pre-fabricated single building for each of the two gas turbines, respectively to the north of the generator bay of the gas turbine building.

5.6.5. E, Natural Gas Reducer Station

In which the equipment for reducing the mains side gas pressure, the reheating of the gas after expansion and the gas flow metering are accommodated: the building is located to the south east of block H near to the power station perimeter fence.

5.6.6. F, Pipe and Cable Bridge

For accommodating the condensate, feedwater and cooling water pipes as well as the energy and signal cables between the topping gas turbine plant and the lignite block H.

5.6.7. G Flue Gas Ducts
From the gas turbines to the waste heat/water pre-heaters and on to the existing stack in block H

5.6.8. H Waste Heat/water Pre-Heaters
Outdoor installation

5.7. Environmental Protection, Environmental Friendliness
When burning natural gas in the gas turbines, lower CO_2, dust and SO_2 emissions are produced per generated kilowatt-hour in comparison with other fossil fuels: therefore the legal emission limits can therefore be complied with without additional flue gas cleaning plants. When the combined heat and power generation (CHP) circuit is switched on the heat for the power station process is provided to the existing lignite blocks in addition to electricity and the used fuel is therefore exploited up to about 90%.

The plant will be erected on the premises of the Weisweiler power station and will use the existing infrastructure therefore minimising environmental impact as little as possible. This plant is designed and built according to the state of the art and current environmental protection laws.

In the course of the approval procedure, the approval authorities must carry out an environmental impact inspection based on the environmental impact analysis submitted by the applicant.

The following test results are given for different criteria:

5.7.1. Air Purity
The main air pollutant in the combustion of natural gas is nitrogen monoxide (NO_x). These nitrogen oxides are produced in the combustion part of the gas turbine.

It had to be proved that the NO_x emissions emanating from the Weisweiler power station as a whole and from the topping gas turbine plant fall below the legal limits.

5.7.2. Noise Protection
The conception of the new topping gas turbine plant was that the noise emitted can not be heard or measured in the neighbouring housing estates. This means that the recommended noise limits for these assessment criteria are reduced by at least 10 dB.

5.7.3. Vibrations
Vibrations are minimised in gas turbines and transfer of any residual vibrations to the foundations is prevented by damping devices. Therefore no vibrations are perceivable in the immediate vicinity of the plant.

5.7.4. Water
Because of the combined operation of the topping gas turbine plant with the existing 600 MW lignite blocks and the resulting extra power, a greater amount of heat will have to be rejected through the cooling towers. Since this takes place partly by evaporation of water in the cooling tower, the resulting deficit in the cooling water must be replaced. The amount drained additionally to avoid salt enrichment in the cooling circuits must also be replaced.

On the whole sufficient amounts of water are available from the ground water of the Inden open cast mine, the pumping and conditioning capacities of the existing plant are also sufficient.

5.7.5. Climate

The volume of cooling tower plume increases slightly due to the additional evaporation of cooling water, but there are no significant meteorological effects as a result.

5.7.6. Waste water

Additional waste waters mentioned are above from the cooling circuits of the lignite bocks and are combined with the rain water from the roof and road areas of the topping gas turbine plant. The collection, treatment and drainage of this water take's place using the existing drain and conditioning systems, which has sufficient capacity.

The permission required for draining the additional water after clarification into the drain system is obtained in a separate procedure.

The waste water from cleaning the gas turbine compressors offline comprises detergents containing tensides and is collected in closed systems and disposed of by a specialist company.

5.7.7. Waste

There is no process-related waste from the topping gas turbine plant. The air intake filters are renewed after a certain amount of operating hours and sewage and other wastes similar to domestic waste are properly disposed of by a specialist company.

5.8. Impact of Greek Lignites on Repowering Plant

The repowering of an existing lignite fuelled unit with a gas turbine topping cycle as described above has no influence on the firing system of the boiler.
It is an additional measure, using an independent fuel for the gas turbine cycle. The systems are coupled on the water steam cycle only.

5.9. Technical Data

5.9.1. Performance Data per Plant Line

Furnace heating power GT (Maximum at –10°C = 594 MW)	MW	532.2
Fuel requirement GT at heating value 45.140 kJ/kg	t/h	42.4
el. net power GT	MW	188.7

5.9.2. Transmitted Heat

In lignite block of which	MW	284.0
- Condensate	MJ/s	127.4
- Feedwater	MJ/s	156.6
el. Extra power lignite block	MW	80.3

5.9.3. Efficiencies per Plant Line

Net efficiency GT	%	35.5

Net efficiency Extra power disc GT + extra power lignite block	%	50.5
Total utilisation factor	%	89.0

5.9.4. Emission Data per Plant Line

Exhaust gas flow GT (Dry in normal state)	m³/h	3,360,000

Emitted substances

-	NO_x (as NO_2)	mg/m³	75.0
-	CO	mg/m³	100.0

Stack height	m	160.0

5.9.5. Total Topping Gas Turbine Plant

Area requirement	m²	6,000
Water requirements for evaporation and flooding	m³/h	680.0

5.9.6. Waste Water

-	From add. flooding cooling water	m³/h	140.0
-	Rain water	m³/min	2.2

6. Flue Gas Desulphurisation

6.1 Development of the FGD Technology in Germany

Germany has many years of experience with the planning and operation of FGD plants. On account of the legal restrictions of the German large furnace plant directive (GfAVO), coal-fired power stations with a capacity of more than 100 MW may only be operated since 1988 with FGD in compliance with specific SO_2 emission limits. Operating faults in the FGD which may lead to bypassing the FGD (bypass mode) are also governed by the GfAVO and are only permitted for a limited period of time. If the FGD plant cannot be returned to service within this limited period of time, then the whole power station will have to shutdown. In principle, these specifications correspond with the EU Directive 2001/80/EC of 2001 which is valid for all EU member states. The FGD technology has been developed further to meet these high demands. As operating experience has shown, the FGD is now a very reliable part of the plant and achieves high availability. With the right planning and proper operation, the FGD does not restrict power station operation even under the very strict legal emission conditions.

A total of about 50,000 MW of power station power are operating with FGD in Germany today. The first large-scale technical, commercial FGD in Germany went into operation at the end of the 1970s/beginning of the 1980s in newly built power stations.

The above mentioned GfAVO then became law in 1984 which planned to limit the pollutant emissions for all coal power stations in Germany. Based on this directive, FGD became obligatory not only for new power stations but also for existing power stations as a retrofit. The time span for retrofitting was 5 years.

More than 85% of the FGD built in Germany up to the end of the 1980s were lime/limestone wet flue gas desulphurisation plants with production of a usable gypsum end product. This technique became standard because its investment costs, availability and space requirements had great advantages over other competing flue gas desulphurisation processes. These advantages were also the reason why this technology has been used in more than 90% of FGD plants in Europe.

6.1.1. Lime - Limestone

Whilst the first FGD scrubbers delivered at the beginning of the '80s were still operated as milk of lime scrubbers (raw product: quick lime), later FGD scrubbers were mainly designed as limestone wet scrubbers. The reasons for changing over to limestone were economic. The raw material costs for powdered lime stone for each ton of SO_2 removed is 50% that of quick lime. Limestone wet scrubbers require an absorber sump of about twice the size (necessary dwell time for the dissolution of the limestone particles) and a much higher absorbent circulation. However, the saving due to the low absorbent costs are greater than the extra costs.
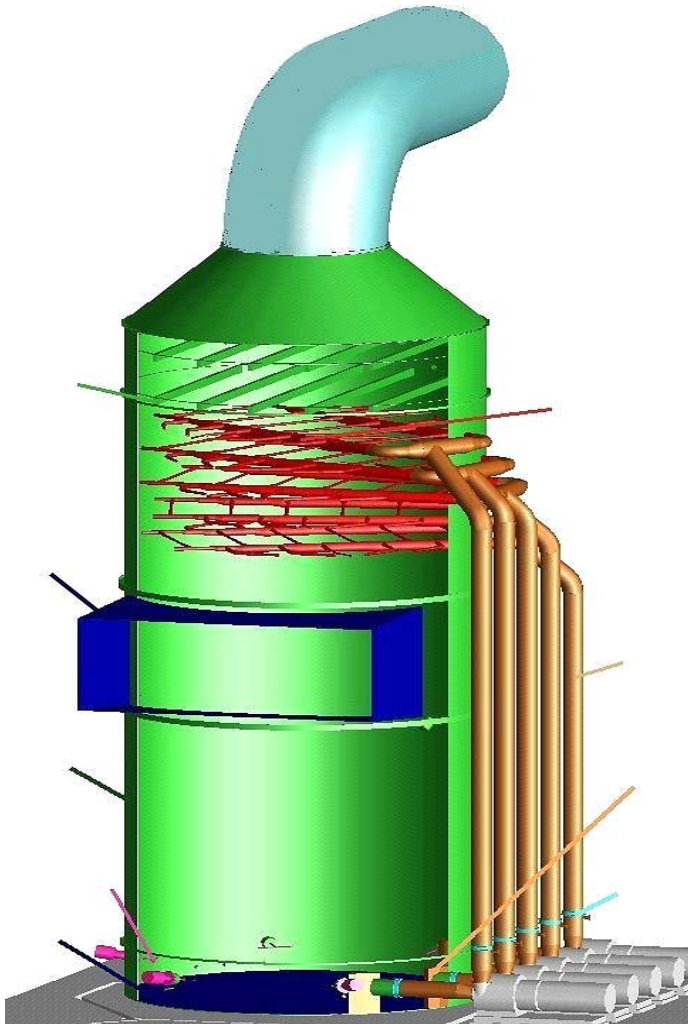

Figure 30: Limestone spray tower scrubber

6.1.2. Gypsum Dewatering

The first FGDs delivered at the beginning of the 80s were equipped with gypsum dewatering which consisted of a gypsum settling basin for pre-thickening and then separation of the water using centrifuges. The FGD's which went into operation from 1987 were usually equipped with hydro-cyclones and belt filters. The reason was the

low investment costs of the belt filter/hydro cyclone system and its low maintenance cost.

6.1.3. Reheating – Discharge Via Cooling Tower

The large furnace plant directive (GfAVO) prescribed a temperature of the flue gases to be discharged of 72°C at the mouth of the stack. This required reheating of the water steam-saturated flue gases for the case of stack discharge.
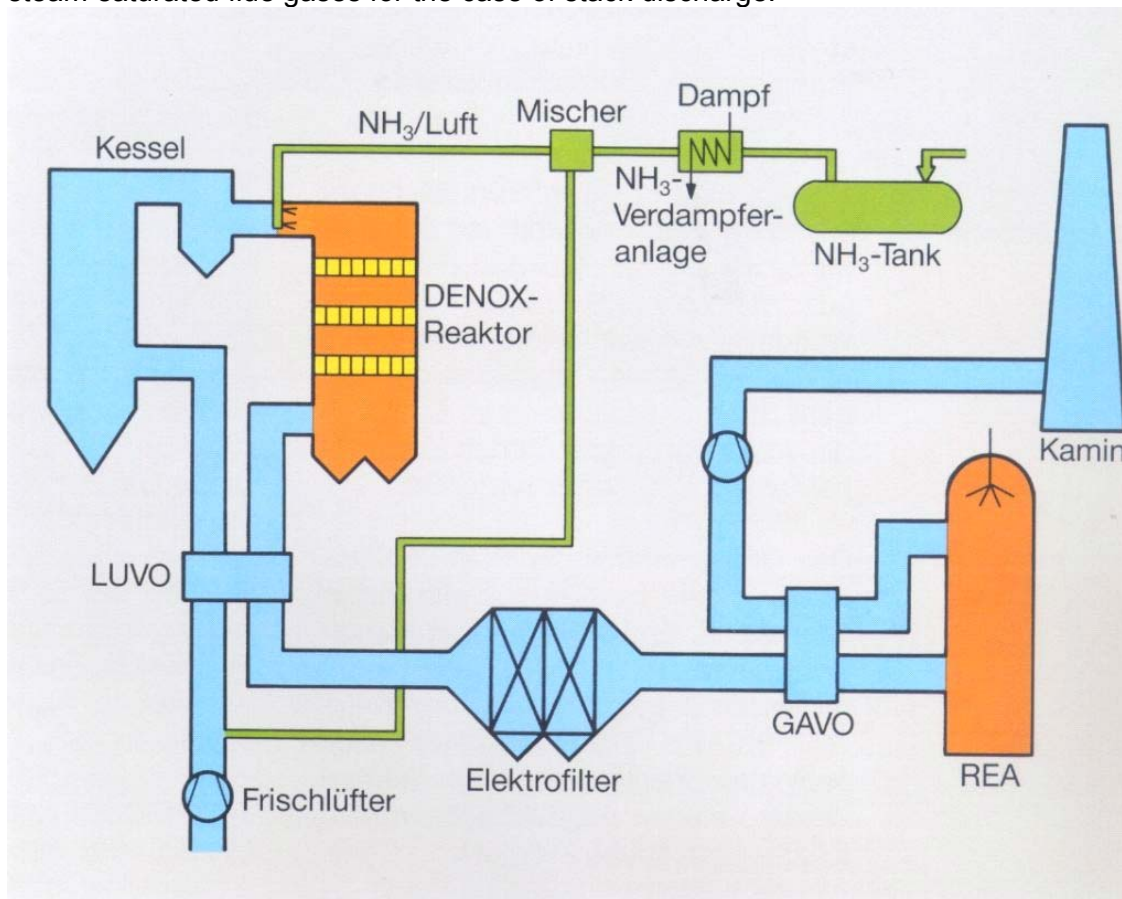

Figure 31:

Regenerative heat exchangers were used in a very large number of plants which take residual heat from the flue gas before the scrubber and add it to the flue gas again on the cleaned gas side after the scrubber. This is a very expensive technique due to the complicated ducting and the additional heat exchanger. The operating costs are also very high because of the additional flue gas pressure loss and the maintenance and repair costs for the heat exchanger system.

As an alternative to this, the reheating was implemented in some FGDs with steam-heated heat exchangers. This did have the advantage of lower investment costs but the disadvantage of constantly high energy costs.

In the 80s an FGD plant built by the Hölter company went into operation where the exhaust was in FGD, the natural draught wet cooling tower of the model power station in Völklingen. The positive results from measurements, especially the proof that the flue gases are carried with the cooling tower plume in the higher air layers than with heated flue gases via the stack, led to this flue gas discharge being become as standard in the GfAVO. The discharge of the cleaned flue gases with the cooling tower plumes from natural draught wet cooling towers was patented by Saarberg/Hölter. The cooling tower discharge also became a low-cost alternative to reheating.

Figure 32: FGD Boxberg (Germany) – Cooling Tower Discharge

Figure 33: Cooling tower introduction of the flue gases, Florina power station, Greece

Since then, most of the FGDs (heating power stations Völklingen/Fenne, Weiher) built at the Saarberg factory in 1987/88 had cooling tower discharge. In 1987/88, the RWE lignite power stations where a natural draught wet cooling tower existed were also retrofitted with a FGD with discharge of the cleaned flue gases via the cooling tower on approx. 70% of the power station power (approx. 7,000 MW). The cooling tower discharge route is much cheaper and much less maintenance intensive than reheating

with FGD-re-gas pre-heater or FGD-steam pre-heater. It also avoids other problems of the heating system such as fouling, leaks and problems due to increased SO_2 slip.

The percentage of FGDs with cooling tower discharge in Germany is about 40% with all new built power stations designed with this technology.

6.1.4. Gypsum Utilisation

The gypsum created in the FGD lime/limestone wet scrubbers is almost always used in the building and cement industries. According to a survey by VGB in 2004 the annual gypsum production is about 7.8 million tons. About 70% of this comes from lignite power stations (Rhineland, East Germany), the rest from had coal power stations. The FGD gypsum has almost completely replaced natural gypsum in the market place.
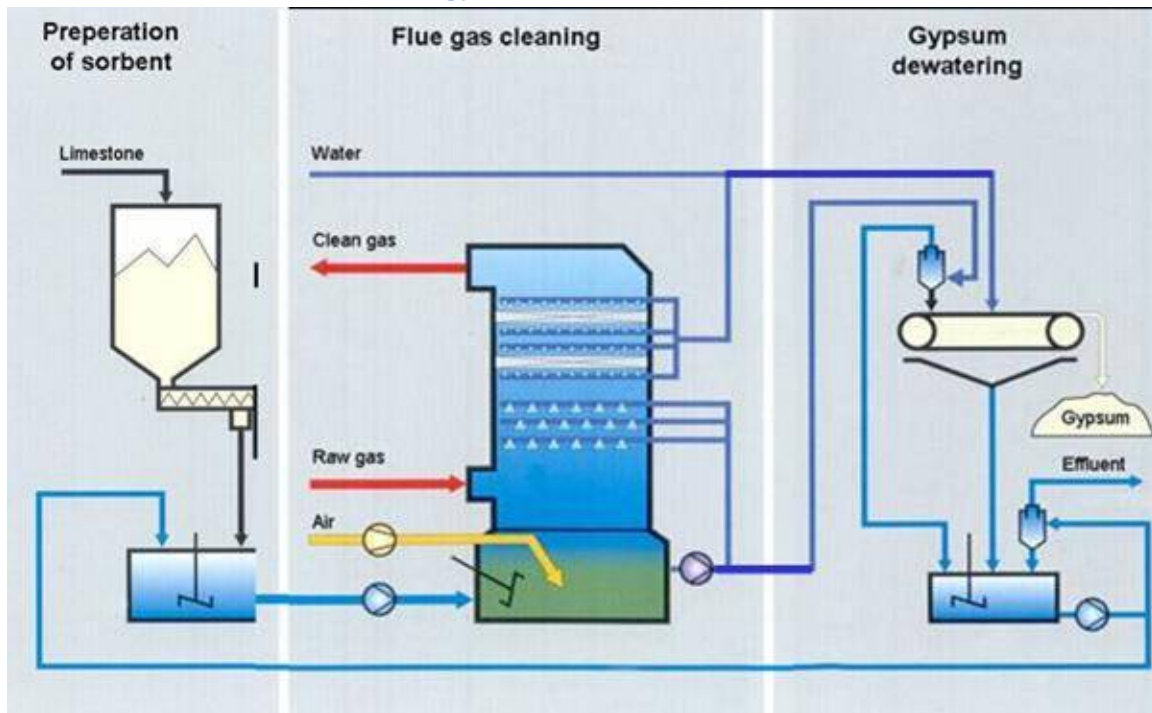
6.2. Current FGD Technology

Figure 34: Standard procedure – today's FGD technology

The modern FGD process uses spray tower scrubbers with limestone as an adsorption agent and gypsum as the end product.

Limestone is supplied depending on local conditions either as powdered lime or in lump form. Provisions must be made on site for grinding if it is delivered in lump form.

In spray tower scrubbers, the flue gas enters the scrubber above the scrubber sump and then flows up in the opposite direction to the scrubbing fluid sprayed in at the top. The acid gas components SO_2, HCl and HF are separated by intensive contact with the scrubbing fluid. Any entrained scrubbing fluid drops are separated in a two-stage mist eliminator above the scrubbing zone. The cleaned flue gas leaves the scrubber cooled and steam-saturated. The scrubbing fluid is collected in the scrubber sump after falling through the absorption zone and has sufficient dwell time there for regeneration before being re-injected into the gas chamber by the circulation pumps.

Lime suspension is added continuously in the scrubber sump according to the

consumption. With the addition of air, the reaction product gypsum is formed in large crystal form and can be discharged continuously.

The scrubbing suspension has a solid content of approx. 13% and must be stirred continuously to avoid settling.

The agitators for this are located at the sides of the scrubber sump below the sump level. The oxidation air necessary for forming the gypsum is fed in by air lances on the pressure side of the agitators. This produces fine air bubbles which are distributed by the directional flow in the sump.

The discharge of the crystalline reaction product gypsum takes place via a two-stage solid/fluid separation. Thereby, the suspension is concentrated in hydro cyclones to approx. 50 wt.% solid content and then placed on belt filters where water is removed to a residual moisture of ≤ 10 wt.-%. The gypsum has a suitable consistency for storage, transport and use in the gypsum or cement industry after the belt de-watering.

Fresh water must be fed to the process continuously to match the consumption.

Waste water must be discharged to discharge soluble reaction products and inert substances which would become enriched in the system. The chloride content of the scrubbing solution is usually used as the control parameter.
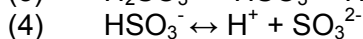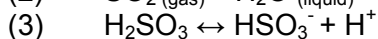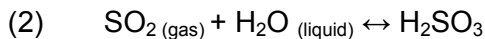
6.2.1. Chemistry of the FGD

The FGD reactions can be described by the following summary formula:

(1) $CaCO_3 + SO_2 + 2H_2O + \frac{1}{2} O_2 \rightarrow CaSO_4 \cdot 2H_2O + CO_2$
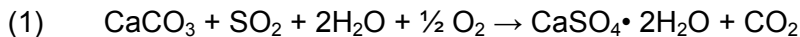
For a better understanding of the process it is also important to examine the intermediate stages.
The first step is the absorption of the gaseous SO_2 in the scrubbing fluid.
SO_2 in watery solution leads to a drop in the pH value. The following equilibra are formed:

(2) $SO_{2\,(gas)} + H_2O_{\,(liquid)} \leftrightarrow H_2SO_3$
(3) $H_2SO_3 \leftrightarrow HSO_3^- + H^+$
(4) $HSO_3^- \leftrightarrow H^+ + SO_3^{2-}$

The separated SO_2 is bound by the dissolved limestone in the solution. A drop in the pH value which would hinder further absorption is thus avoided.
$CaCO_3 + 2SO_2 + H_2O \rightarrow Ca(HSO_3)_2 + CO_2$
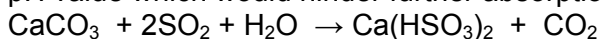
The desired end product gypsum (calcium sulphate anhydrate) is finally obtained by oxidation.
$Ca(HSO_3)_2 + O_2 + CaCO_3 + 3H_2O \rightarrow 2(CaSO_4 \times 2H_2O) + CO_2$
Part of the oxygen required comes from the flue gas (as excess air), however, the greater part is supplied by blowing air into the scrubber sump.
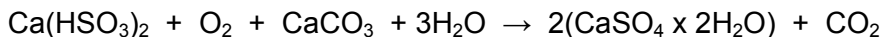
Apart from SO_2 there is also HCl and HF in the flue gas. These are scrubbed out and become bound with the limestone analogously with the SO_2:
(5) $CaCO_3 + 2\,HCl \leftrightarrow CaCl_2 + CO_2 + H_2O$
(6) $CaCO_3 + 2\,HF \rightarrow CaF_2 + H_2O + CO_{2\,(gas)}$
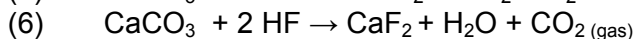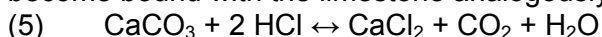
6.3. Differences in the FGD Technology in Lignite Power Stations and   hard Coal Power Stations

The FGDs in lignite power stations and hard coal power stations have several basic differences which influence the FGD process, the materials used and the recycling of the power station products.
These differences are:

- chloride content of the coals and FGD waste water discharge
- ash recycling or ash dump
- flue gas volume flow
- sulphur concentration and variation of the sulphur contents
- gas temperature and flue gas moisture before the FGD absorber
- scrubber temperature and the life of the scrubber corrosion protection, i.e. of the rubber coating

6.3.1. Chloride Content of the Coals and FGD Waste Water Discharge and Ash Recycling or Ash Dump

There is a great difference in the FGD waste water discharge between the lignite power stations and the hard coal power stations. Generally a waste water flow must be discharged from the scrubbing process in both FGD versions so that soluble salts (chlorides) separated in the absorber can be removed. The chloride content in the lignite is low in comparison with hard coal, therefore less waste water occurs.

Use of the dry ash from lignite power stations in the cement industry or road construction is not possible because of the unfavourable composition of the ash, the ash has a very high free lime content so is disposed of in the excavated open cast lignite mine.

The FGD waste water is used to wet the dry ash to prevent dust emissions when dumping the ash in lignite open cast mines. The percentage of FGD waste water is about 10 to 20% of the dry ash volume.

The internal wetting of the ash on the power station premises or in the open cast mine with a partial flow of the FGD circulation water from the hydro cyclone is also known as "operation with out wastewater". The FGD waste water is drawn from a part of the flow of the hydro cyclone overflow and is mixed with the ESP dry ash.

Unlike the FGDs in lignite power stations, it is not possible to wet the ash in hard coal power stations. This is because the chloride loading introduced into the FGD with the coal is about five times higher on average and therefore the waste water flow to be discharged is also 5 times higher than in a lignite FGD. For example, the waste water volume flow for a 300 MW_{el} hard coal power station block is about 15 m³/h, whilst for a lignite block of the same size it is only 3 m³/h. In terms of mass, there is an excess of FGD waste water in the coal power station in relation to the produced ash. In addition about 80% of the hard coal dry ash is used in Germany in road construction or as an additive for concrete (ash quality subject to certification) so that wetting with waste water is inappropriate.

In the hard coal FGD the discharged FGD waste water (partial flow of the hydro cyclone overflow) must therefore be treated in a waste water treatment plant (WCP) before it can be discharged into the pre-flooder. Heavy metals are separated in the waste water treatment plant by adding alkalis and flocculation agents. The sludge produced in the waste water treatment plant is usually mixed with the coal supply for burning so that no additional material is produced from the FGD process that needs disposal.

6.3.2. Flue Gas Volume Flow

At equal power station efficiency and plant block size, the wet flue gas volume flow in the lignite power station is about 40% higher than in a comparable hard coal power station. That means that the flue gas ducts and the absorber tower in the lignite power station must be built with a diameter that is 15 to 20% bigger. The cause is the different calorific values and compositions of the lignite and hard coal. Lignite has a much higher water content (more than 50%) than coal (approx. 10%).

6.3.3. Sulphur Content

The sulphur content of the raw coals in lignite and hard coal power stations may be at about the same level but produce different SO_2 contents in the flue gas. For example, an SO_2 content in the dry flue gas of 2,000 mg/m³ is produced with a German hard coal with a sulphur content of 1%. A Rhenish lignite with 1% sulphur produces SO_2 content at 5,500 mg/m³.

The reasons are that the lignite has a higher water content and therefore a higher fuel mass, flow is required to generate the same duty because of the much lower lignite calorific value in comparison with hard coal. This increases the SO_2 loading in the flue gas.

The increased SO_2 content in the flue gas with lignite results in the absorber having to be operated with an increased circulation volume flow of scrubbing fluid. For the above mentioned example of 1% sulphur in the coal, the circulated suspension scrubbing volume flow in a lignite FGD is about double that in hard coal FGD at the same SO_2 emission limit. The specific energy requirement for the desulphurisation is also about double.

The sulphur content in the lignite may fluctuate greatly which has to be taken into account in the design of the FGD absorber. This must be designed for the maximum sulphur content which may occur. As the sulphur content varies, circulation pumps are switched on or off to optimise the power requirements. These problems were also largely solved in German lignite FGDs partly by automation of the switching criteria for the absorber circulation pumps.

The sulphur content is usually constant in hard coal. It only changes depending on which coal is being used (Imported coals to Germany have sulphur contents typically of 0.5 to 1.3%).

Therefore the FGD operator can adjust easily the process conditions to the changed sulphur conditions in the flue gas because the coal to be used is known beforehand.

6.3.4. Flue Gas Temperature, Moisture

There are great differences between the lignite and hard coal fired stations with regard to the flue gas temperature after the air pre-heater and the flue gas moisture.
In the lignite fired power stations the flue gas temperature is usually between 160°C and 190°C, whilst in the hard coal fired power stations the temperatures are between 125°C and 150°C. The reason for this is the required metal higher plate end temperature in the air pre-heater in lignite power stations to avoid saturating and fouling by sulphuric acid condensing in the flue gas and the simultaneous reaction with the alkaline fly ash when the flue gases cool down (acid dew point).

The increased exhaust gas temperature means, however, that more water evaporates in the lignite FGD absorber than in the coal FGD absorber and a higher operating temperature is required in the scrubber. A further increase in the operating temperature is produced in the absorbers of lignite power stations by the higher flue gas moisture. The flue gas moisture before the scrubber in the hard coal power stations is about

7%, the flue gas in the lignite power stations has a moisture content of about 20 to 25%. In conjunction with the above mentioned different flue gas temperatures, an adiabatic saturation temperature is set in the scrubber which is about 50°C in the FGD scrubber in hard coal power stations and about 70°C in lignite power stations.

6.3.5. Rubber Coating / Scrubber Material

The above mentioned different operating temperatures in the FGD absorbers in lignite and coal power stations have also had different effects on the scrubber corrosion protection rubber coating in the FGD plants built in Germany. If you compare the two types of fuel in the FGD absorber:

- Hard coal FGD: temperature 50°C, flue gas moisture in the scrubber 10%
- Lignite FGD: temperature 70°C, flue gas moisture in the scrubber 28%

There is a considerable difference in the thermodynamic properties. This resulted in the corrosion protection failing earlier in operation on the lignite FGD absorbers in Germany. Because of the higher temperature and the higher steam content in the flue gas of the lignite absorbers, the steam diffuses more rapidly through the rubber to the cold steel wall of the absorber and leads to the formation of water bubbles. The rubber also ages faster due to the higher temperatures. The rubber coatings have had the following service life in the German FGDs:

- Hard coal FGD: 12 to 15 years
- Lignite FGD: 7 to 10 years

The short service life in the lignite FGD led to the development of alternative solutions in addition to the development of new, improved rubber coating qualities. A frequently used and successful alternative is stainless steel lining of the FGD absorber. But this has the disadvantage of higher investment costs.

6.4. Influence of the Greek Lignites and Imported Coals on the FGD Process in the Power Station

6.4.1. FGD Data for Greek Lignite's

In comparing the most important coal and flue gas-relevant data of the Greek lignite's with that of the data for the Rhenish and East German lignite's, there is little difference in the design conditions for a FGD. The Greek lignite's fuel parameters most of concern for the design of the FGD are:

	Florina	Ptolemais	Drama
Calorific value, kJ/kg	7890	5368	4380
Sulphur content, %	0.7 (0.4-2.7)	0.4	0.1(1.63)
Water content, %	37.4	51.1	57.8
Ash content, %	26.8	17.3	16.5

In comparison with the typical values of a Rhenish lignite in Germany, there are no significant differences in the most important parameter.

6.4.2. Rhenish lignite

Calorific value, kJ/kg: 8,700
Sulphur content, %:   0.4-1.0
Water content, %:   53.0
Ash content, %:   5.0

The major difference is the high ash content of the Greek lignite's. The sulphur contents of the Greek coals are much lower in comparison with the earlier design values for the FGDs in Megalopolis and Florina. These values were published in the International Journal of Coal Geology, "Coals of Greece", 58 (2004).

6.4.3. Florina

For the Florina power station, the PPC has assumed much higher sulphur values for the design of the FGD, cf. the values in brackets (State of the Art Wet FGD System for High-Sulphur Fuels in Florina/Greece, Alstom/PPC). In practice, these maximum values in the sulphur content will occur relatively rarely.

The 330 MW_{el} power station Florina of the PPC, in operation since 2003, only produces SO_2 concentrations in the flue gas of 6,400 mg/m³ on average before FGD, although the maximum SO_2 design value is 11,500 mg/m³.

This means that the sulphur values of Greek lignite's are subject to similar fluctuations to those of the German lignite power stations. For the PPC power station Florina, the average sulphur content in the coal, derived by calculation from the SO_2 operating values is about 1.1% S. This value is still about 50% above the value specified in the above publication. These values are summarised again for Florina in the following table:

	Sulphur content coal	SO_2 content flue gas
Geolog. data Florina	0.7%	4,260 mg/m³
Design PPC	0.4 – 2.7%	max. 11000 mg/m³
Operating values	1.1%	6,400 mg/m³

Since no other average sulphur contents of the raw coal Florina are available for the study, the value (S = 0.7%) published by the geological institute is used below for the FGD balance. The most important inlet and outlet mass flows for the FGD are determined from this and with these results reference is made to the other sites Ptolemais and Drama.

Below, the most important FGD-relevant data for the different Greek power stations sites are determined as examples for a 300 MW_{el} power station equivalent. These data can be converted directly to other power station ratings.
The following **assumptions** are made for the **FGD Florina**:
Power station size: 300 MW_{el}
Power station efficiency: 40% gross
SO_2 emission limit value (EU standard): 200 mg/m³
Dust emission limit value (EU standard): 30 mg/m³

From the above mentioned data the average FGD-specific data for the power station example of **Florina** can be determined. From the above lignite calorific value and the

plant efficiency gives a power station efficiency – coal mass flow: 330 t/h

Based on calculating the products of combustion gives a flue gas volume flow of 1.3 million m³/h, STP, wet or 1.08 million m³/h , STP, dry

The most important FGD-relevant design and process variables

SO_2 – mass flow	4.6 t/h
SO_2 – raw gas content	4,260 mg/m³ , STP, dry
Limestone mass flow	7.2 t/h
Gypsum mass flow	12.4 t/h, dry

In addition, the calculation provides other variables such as:

- Flue gas moisture: 17 vol.%
- FGD inlet temperature: 170°C
- FGD-SO_2 separation factor: 95.3%
- SO_2 emission freight: 0.21 t/h

The following operating conditions are set in the absorber:

- Absorber temperature: 64 °C
- Evaporated water: 82.2 t/h

The disposal of the ash with the FGD waste water is calculated as follows:

- Dry ash mass flow (80% of the total ash): 62.6 t/h
- FGD waste water volume flow (10% rel. to dry ash): 6.3 m³/h

The following standards are used as a basis for FGD Florina:

- Discharge of the cleaned flue gases with the plumes from the natural draught wet cooling tower
- Wetting of the dry ash with the FGD waste water in an intensive mixer and conveying of the wet ash by conveyor to the open cast mine
- Dewatering of the produced gypsum on a gypsum belt filter press and intermediate storage of the gypsum in a gypsum silo
- Use of the gypsum in the Greek cement industry. If no recycling is possible, conveying of the dewatered gypsum onto the ash remote belt and transport of the stabiliser (ash and gypsum) to the open cast mine.

Comparing the data for the Ptolemais and Drama sites with the above specific FGD figures for Florina reveals:

6.4.4. Ptolemais:

For Ptolemais the specified sulphur contents from the coal analyses are at an even lower level than for Florina. They are only 0.4% on average according to the publication.

Because of the lower calorific value, a greater coal mass flow is set for a 300 MW$_{el}$ power station (485 t/h) which is 46% higher than for Florina. However, the sulphur content is about 42% lower than in Florina so that there is a sulphur mass flow is 1.94 t/h.

Because of the higher moisture content of the raw lignite in Ptolemais resulting in a

higher moisture content in the flue gas, a saturation temperature of approx. 70°C is used in the flue gas scrubber, which is 6°C higher than the Florina example. This increase is not critical for the FGD process, however, but may affect the decision on the corrosion protection in the FGD absorber.

FGD-relevant mass flows and concentrations occur for a 300 MW$_{el}$ power station on the whole

SO_2 – mass flow	3.9 t/h
SO_2 – raw gas content	3,610 mg/m³ , STP, dry
Limestone mass flow	6.1 t/h
Gypsum mass flow	10.5 t/h, dry

6.4.5. Drama:

The average sulphur content is only 0.1% according to the specifications of the geological institute. The value expected from analyses is much higher, however, namely 1.63%. The value of 0.1% is doubtful and should be confirmed by appropriate new analyses so that the FGD design for a new lignite power station is guaranteed.

The calorific value of the coal for Drama is at a much lower level than for Ptolemais and gives a coal mass flow which is 87% higher than in Florina (300 MW$_{el}$ = 594 t/h). This gives a total sulphur mass flow to be separated in the FGD of 0.59 t/h when the sulphur content of only 0.1% is assumed. The moisture content of the Drama coal is very high at 58%. A saturation temperature of 72°C is calculated in the scrubber for this.

FGD-relevant mass flows and concentrations occur on the whole

SO_2 – mass flow	1.2 t/h
SO_2 – raw gas content	1,110 mg/m³ , STP, dry
Limestone mass flow	1.9 t/h
Gypsum mass flow	3.2 t/h, dry

If the assumed sulphur values of 0.1% do not apply and the determined 1.67% is realistic, an average SO_2 concentration in the flue gas of approx. 18,000 mg/m³ would occur for a power station in Drama. Peak SO_2 values of 25,000 – 30,000 mg/m³ are then to be expected due to the variations in the sulphur content of the Greek lignite's. That would mean that Drama exceeds the sulphur values of the power stations Maeh Moh (Thailand) and Maritsa East 2 (Bulgaria) by 50%. With this background the question of whether the high expense of FGD and its required energy and the logistical transport problems justify building such a new power station. As already mentioned, an exact analysis of the sulphur contents of the coals is necessary for specification of the FGD-relevant minimum and maximum values. The same FGD standards apply for the FGD sites Ptolemais and Drama as for Florina.

6.4.6. FGD Data for Imported Hard Coals

For the design of an FGD with power station site in Greece, the following imported coals with their characteristic data are available.

Imported coals with their characteristic data's

	Forando (SA)	Taezhny (Russ.)	Taldinskaya (Russ.)
Calorific value, kJ/kg	24,823	25,329	25,325
Sulphur content, %	0.76	0.4	0.29
Water content, %	9.2	9.0	10.6
Ash content, %	13.0	10.0	8.85

If you compare the above figures with each other it is clear that the calorific values are on about the same level and therefore the flue gas volume flows for the different coals to be determined for an FGD design are about equal. Only the sulphur contents of the selected imported coals deviate strongly and are at a very low level, especially in the case of the two Russian coals.

To determine the FGD-relevant data, the same power station size (300 MW$_{el}$), the same efficiency (40% gross) and the same EU emission specifications (200 mg/m³ SO$_2$, 30 mg/m³ dust) are assumed as in the three lignite power stations.

For a coal FGD this gives:

- Coal mass flow for the three coals: 108 t/h
- Flue gas volume flow: 950,000 m³/h STP, wet
- Flue gas moisture: 7%
- FGD inlet temperature: 130°C

Important FGD-relevant concentrations and material flows result

SO$_2$ – mass flow	0.62 – 1.64 t/h
SO$_2$ – raw gas content	700 – 1,820 mg/m³ , STP, dry
Limestone mass flow	0.97 – 2.56 t/h
Gypsum mass flow	1.66 – 4.40 t/h, dry

The other process variables are:

- FGD-SO$_2$ separation factor: at least 90%
- SO$_2$ emission freight: 0.06 – 0.2 t/h

The following operating conditions are set in the absorber:

- Absorber temperature: 50°C
- Evaporated water: 43.8 t/h

The waste water volume to be discharged from the FGD system into a pre-flooder is calculated for a coal FGD from the necessary operating chloride concentration in the absorber suspension and the chlorine content of the coal. The chlorine content of the coal for Taezhny coal is specified with 0.028%. In a permissible chloride content of the suspension of 15 g/l chlorides a chlorine mass flow of 30 kg/h is calculated. This gives a waste water volume flow of 2 m³/h to be discharged.

It is recommended that the design waste water volume flow be greater because other coals on the world market have 5 to 10 time's higher chlorine content. The waste water treatment plant (WCP) should therefore be designed for a greater capacity i.e. waste water volume flow: max. 15 m³/h.

The heavy metal contaminated gypsum sludge in the FGD waste water from in the WCP is drained of water and then added to the coal in the power station so that no remaining product is produced which needs disposal. The amount of sludge for a 300 MW hard coal block is 150 kg/h, dry. The wet sludge from the high-performance thickener can be transported directly to the coal bunker.

The dry ash occurring in the process (approx. 80% of the total ash) is recycled in the cement industry. The dry ash mass flow corresponds to 9.7 – 14.0 t/h

Recommendation for the recycling of the gypsum and improvement of the gypsum quality:

The SO_2 content in the flue gas is at a very low level (700 mg/m³ SO_2) especially in the Russian coals. To prevent the gypsum being contaminated by ash from the electrostatic precipitators (ESP) and being difficult to dewater on the gypsum belt filter, the dust content in the flue gas after the ESP should be reduced to at least 5% of the SO_2 concentration value. This gives a design emission for the ESP of ESP: 30 mg/m³, STP, dry.

The following standards are used as a basis for the FGD in a coal power station:

- Discharge of the cleaned flue gases with the plumes in the natural draught wet cooling tower
- Certification and disposal of the produced dry ash in the cement industry
- Drainage of water from the produced gypsum on a gypsum belt filter and intermediate storage of the gypsum in a gypsum silo
- Use of the gypsum in the Greek cement industry.
- Return of the WCP sludge with the coal stream for burning in the furnace room

Comparing the figures assumed for a FGD in a block with Greek lignite's, e.g. Florina site, with the FGD-relevant process variables in a hard coal block, there are differences in the sulphur flue gas values, the amount of limestone and the gypsum for disposal. These differences also exist in the absorber circulation volume necessary for the SO_2 separation and in the energy required for the FGD process.

To achieve economic absorber size for the Greek lignite power stations the maximum sulphur value should be limited as in the German lignite power stations to a value based on the flue gas flow average or the coal bunker average. This avoids over sizing in the FGD.

When dimensioning a FGD for an imported coal power station it is advisable to design the FGD for higher sulphur contents of the coal than the specified coals because this enables a wide range of world market coals to be used in the future.

6.5. Lignite optimised plant technology (BoA) for a FGD

FGD plants were first put into operation in the Rhenish lignite power stations in 1987 so there is 18 years of experience.

Most of the FGD plants based on limestone wet scrubbing had faults and failures due to the following:

- Deposits and fouling
- Failure of the absorber corrosion protection rubber coating and the internal coatings of the flue gas ducts

Deposits and hard fouling mainly occurred on the special design features of the absorbers, e.g. in the conical head area, conical sump extension, in the flue gas duct inlet, on support structures and installations, in the sump of the square absorber. Consequential damage occurred when the deposits exceeded certain sizes and the larger deposits became loose and fell off. The results were:

- Destroyed absorber rubber coatings
- Corroded box carrier in the absorber
- Bent agitator shafts in the sump
- Blocked nozzles (especially spiral nozzles) and blocked nozzle lances
- Blocked grids

In some scrubbers there was premature failure of the corrosion protection rubber coating due to wetting and formation of blisters on the steel surface. This failure was most prevalent in the pre-vulcanised chloroprene rubber coatings. Other rubber qualities achieved longer service lives so that they only had to be changed after a long time in operation. A rubber coating of a non-pre-vulcanised bromide-butyl foil achieved the best operating results.

In some flue gas scrubbers, distribution measurements of the SO_2 in the pure gas after the absorber were carried out during the commissioning phase and after the guarantee measurements, similar to the $DeNO_x$ catalysts. The grid measurements revealed strong misdistribution of the SO_2, especially with square scrubbers with aligned nozzle lance arrangements and large distances between the nozzle lance distributors. The result was that the guaranteed degree of desulphurisation was not achieved. The SO_2 misdistribution was due to the mechanical design affecting the flow distribution which leads to an uneven precipitation density over the absorber cross section. In the areas of low precipitation density, the flue gas then effectively flows through a bypass with the result that high SO_2 concentrations occur in the clean gas.

The above knowledge led to the FGD manufacturers rethinking and modifying their absorber designs in discussion with the power station owners. In the mid '90s, this knowledge was captured in invitation to tender specification documents issued by the power station owners for new plants and FGD retrofit. These contain the new design specifications and new material specifications for the corrosion protection of the absorbers:

- Compact absorber dimensions with higher flow velocities
- Specific material specifications for FGD absorbers for coal and lignite power stations
- Design specifications for avoiding deposit zones
- Design specifications for nozzles, screens in front of circulation pumps, agitators, nozzle lances, mist eliminators, etc.

This has developed into an absorber version in the FGDs built from about 1995. This standard is specified as follows for the spray tower scrubbers:

6.5.1. Absorber Jacket/Raw Gas Inlet:
- Cylindrical design if possible without conical sump extension
- Compact absorber dimensions with flow velocities of 4 m/s
- All reinforcement profiles mounted externally, no packing installations
- Continuous flue gas duct bottom rinsing with process water

6.5.2. Absorber Sump:
- Tank agitators distributed around the circumference with about 100 W/m³ stirring power for the sump contents
- At least 4 min. dwell time for the absorber circulation volume
- Free rinsing lances below the agitator shafts and protective covers for the agitator shafts

- Agitator – oxi-air injection
- Flow optimised basket filters in front of the suction nozzles of the circulation pumps with at least 5 times the free cross section of the suction pipe
- Sump quick-emptying pumps with approx. 4 hours emptying time

6.5.3. Spray levels/mist eliminator:

- Spray levels offset to each other at an angle of about 15 °.
- Pipe outlets to nozzles and lances arranged tangentially
- Double eccentric hollow cone nozzles with max. 50 m³/h throughput
- High nozzle density of approx. 1 nozzle/m² cross sectional area, increased number of nozzles in the vicinity of the absorber wall to avoid a flue gas bypasses
- Mist eliminator, 2-stage above the spray nozzle level

Supplementary to the absorber design features, new concepts have been pursued in terms of material technology for the corrosion protection. These concern:

6.5.4. Scrubber Head/Jacket:
Coal and lignite power stations: 4 to 6 mm thick rubber coating as non-pre-vulcanised bromide-butyl rubber foil. For lignite power stations also: C-steel with 2 mm roller plating of Alloy 59 or Hastelloy C-276

6.5.5. Support Girder:
Steel girder plated with Alloy 59; intermediate girder, e.g. in the mist eliminator supports, also as glass fibre reinforced plastic GRP, solid material

6.5.6. Raw Gas Inlet Nozzle:
Alloy 59 solid material or 4mm Alloy 59 roller plated C-steel

6.5.7. Scrubber Floor:
2 x 4 mm rubber coating, quality same as scrubber jacket. For lignite power stations also: Alloy 59 solid material or 4mm roller plated C-steel

6.5.8. Screw Connections:
Alloy 59

6.5.9. Spray Lances/Spray Levels:
GFRP or polypropylene. For lignite power stations also high-grade steel 1.4562 (Alloy 33) or Alloy 59

6.5.10. Mist Eliminator and Rinsing Pipe:
Polypropylene

6.5.11. Absorber Circulation Pipes:
GFRP, GFRP with polypropylene inliner or steel-rubber. For lignite power stations also high-grade steel 1.4529

6.5.12. Agitator shafts/Agitator Propellers/Basket Filters:
Agitator shafts: high-grade steel 1.4529; agitator propellers: Duplex 1.4565; basket filters: High-grade steel 1.4529 or polypropylene

6.5.13. Nozzles:

SiC

6.5.14. Flue Gas Ducts:

GFRP solid material

6.6. Design issues

Whilst the absorber wall and the support girder in the earlier scrubber designs were rubberised, only the absorber wall is rubber coated as a "wallpaper" in the new scrubber designs. This is because the renewal of the rubber coating on the girders and the installations is very time consuming and the costs are about the same as re-rubberising the absorber wall. The girders and installations are therefore clad with an alloy jacket or designed as a roller-plated sheet.

The non-pre-vulcanised bromide-butyl rubber foil with a foil thickness of 6 mm is the optimum rubber coating. This quality has been used for about 6 years in FGD retrofits and new plants for lignite and hard coal FGDs and has been proven in operation. The expected service life for hard coal FGDs is about 20 years and for lignite FGDs about 12 to 15 years (based on full load operating hours of approx. 6,000 h/a).

The flue gas duct inlet, up to about 7 m before the absorber, is designed as a 4 mm thick Alloy 59 roller plating if no heat exchanger system exists (inlet temperatures up to 180°C). This version offers the possibility of rinsing the flue gas duct with process water to prevent deposits and fouling. The alloy cladding is fitted up to about 2 m into the absorber area all around the flue gas duct. In FGDs which are designed with a regenerative heat exchanger system (flue gas inlet temperature about 100°C) a Ceilcote 232 Flakeline coating is used in the area after the heat exchanger up to the absorber inlet. This can be used both in the wet and in the hot, dry areas and guarantees a long service life.

The spray nozzle levels are designed with only one or two GFRP main headers for the distribution of the lances in the absorber. Supports for the headers in the middle of the absorber are usually omitted or there is only one main support in the middle and at the absorber wall if there is no other possible support mechanism. Recently, the spray nozzle levels are being designed with the material PP. According to the plant manufacturers, the investment costs are about 10% below those for GFRP versions. The support girders necessary for PP are along the PP pipes on the bottom and are designed as PP steel-clad hollow girders as they have been used for many years by Munters/Euroform for supporting the mist eliminator elements.

A totally new material concept has been developed for the first time for the BoA2 block being built at the Neurath power station. Here the FGD absorber is being built of concrete and not steel. The internal corrosion protection in the concrete absorber is provided by a double-walled PP system which is incorporated in the concrete shuttering and hooks firmly into the concrete by a PP anchoring system during hardening. The PP plates are then welded tight after hardening of the concrete. A life of 30 to 40 years is expected for this corrosion protection system.

At the end of the '90s a new lignite power station concept with lignite pre-drying by the name of **BoA plus** was developed by RWE as a power station owner. The specifications were a lignite pre-drying with a special fluidising technique, up to a residual moisture content of the raw lignite of 20%. The effect on the flue gas to be cleaned in the FGD is a reduction of the flue gas moisture to approx. 12 vol.%. Other effects are that the flue gas volume drops by about 10% and the components in the flue gas path, flue gas ducts, ESP's and absorbers can be smaller. The reduction in

the flue gas moisture also leads to a lower saturation temperature of 53 °C in the FGD scrubber which allows a low-cost rubber coating to be used as a corrosion protection as in the hard coal FGD absorbers. The flue gas temperature after the air pre-heater can also be reduced because the SO_3 acid condensation temperature is reduced due to the flue gas moisture. The operating conditions for the FGD technology are improved by the use of the BoAplus technology.

New design specifications and material specifications from the BoA-FGD technology allow a longer life and improved SO_2 separation with a lower energy use. These specifications should also be applied to the Greek lignite sites with FGD technology and to new coal sites with FGD in Greece. Some of the BoA metal material concept specifications for the FGD have been implemented in the existing PPC330 MW power station Florina. Therefore, the other specifications (above) can also be used for future Greek coal power stations.

6.7. Conclusion

The issues for flue gas desulphurisation plants for Greek lignite power station sites have been examined. The Florina, Ptolemais and Drama sites have no great process differences to the FGDs implemented in the Rhenish lignite region. For a reliable design of a FGD, the specified coal sulphur contents for the three Greek lignite power station sites should be checked to verify and ascertain the sulphur minimum and maximum values. This applies especially to the Drama lignite site. The BoA FGD technology developed in Germany for the optimisation of the process technology and the materials in the FGD flue gas absorber can be applied to the Florina, Drama and Ptolemais sites. The selection of the materials to be used depends on the design life required.

FGD in a power stations fired with the imported coals also show no great process differences for the Russian and South African coals. The examined coals have a very low sulphur content. However, to enable other imported coals to be used, the FGD should be designed for a higher sulphur content.

For lignite and hard coal power stations with FGD in Greece, the use of the produced gypsum should be sold to the building industry market as is the case in Germany.

7. High-Dust Selective Catalytic Reduction (SCR) of NOx

Most of the $DeNO_x$ catalyst systems went into operation in the coal power stations in Germany in 1988 and so Germany has over 18 years of experience with the operations of SCR plants. The technology itself was developed in Japan, whereby the German plant builders had purchased a license from the Japanese companies.

A total of approx. 20,000 m³ catalyst material has been used for NO_x reduction in Germany. 72% of the catalysts are of the "honeycomb catalyst" type (components ceramic/titanium dioxide), the rest of the catalysts are coated metal plate catalysts. In 98% of the plants the catalyst was arranged in the high dust area after the boiler economiser, it was installed in only 2% of cases in the tail end area with reheating by an FGD-re-gas pre-heater after the FGD. The installation after the FGD was only selected in slag-tap furnaces to avoid catalyst poisoning by enrichment of certain heavy metals or if there was no room for a retrofit in the boiler. Today, only the high dust arrangement is built.
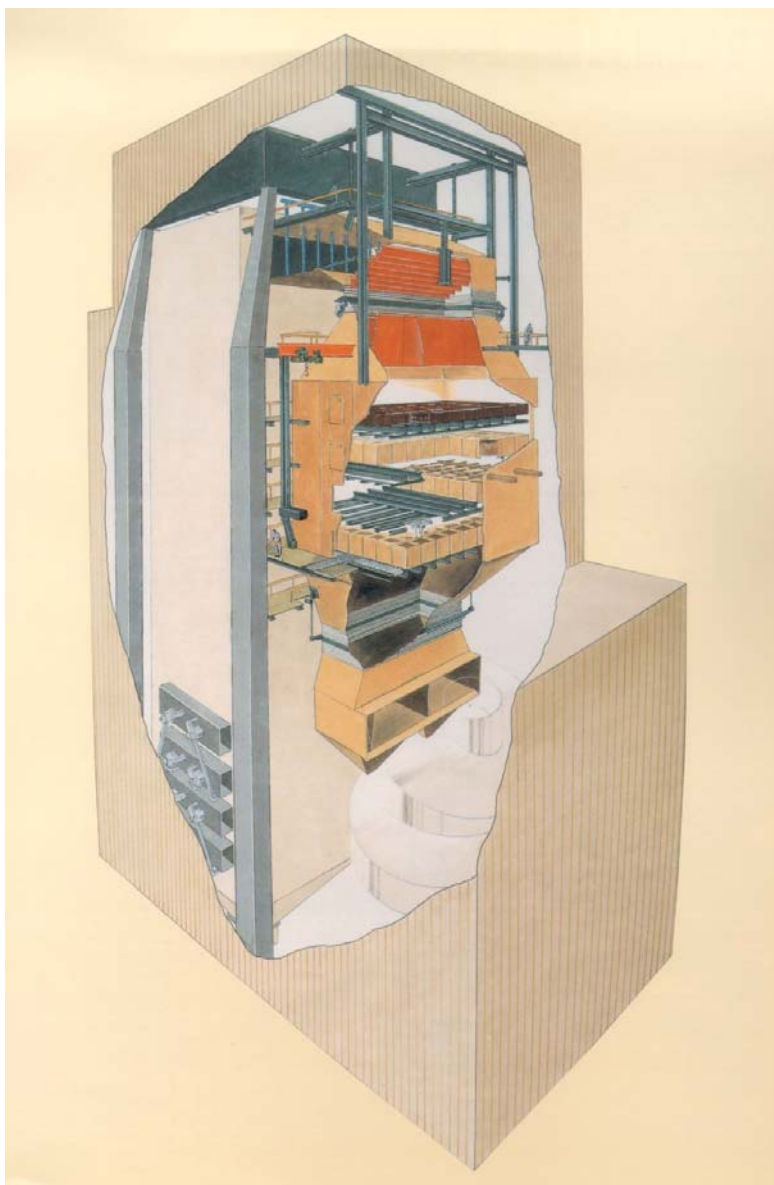
Figure 35: Catalyst arrangement in high dust area

Experience to date with the catalysts is positive and the life of the catalysts is much longer than was originally expected. On average, only 5%, i.e. 1000 m³, of the installed 20,000 m³ cat volume is replaced each year. This means that of the three catalyst layers usually installed, only one layer has to be replaced every 5 to 10 years. With the introduction of the new scrubbing regeneration technology for the honeycomb catalysts at the end of the '90s, the requirement for installation of completely new catalysts material each time was required. Today 50% of the catalysts are being reactivated by the scrubbing regeneration.

The catalyst blocks height 1 m and an area of 0.15 x 0.15 m are accommodated in a steel module of 1 x 2 m. Several modules then form a catalyst layer in the catalyst reactor which can be exchanged accordingly. The reactor usually consists of 2 or 3 catalyst module layers plus an additional reserve empty layer. The reactor is installed after the economiser, before the air pre-heater and operates at STET 340 and 380°C. The reaction between the NO_x and the ammonia (NH_3) takes place in this temperature range. The reaction occurs in the fine pores of the catalyst in the active, acid V_2O_5 centres and an oxidisation reaction i.e. the NH_3 is oxidised by the acid atom of the NO_x into nitrogen (N_2) and water (H_2O).

7.1. Catalyst modules

Aging or poisoning of the catalyst usually results from a chemical deactivation of the acid centres by alkaline fly ash components or certain heavy metals or by blocking or clogging of the fine micro pores.

The NH_3 is distributed evenly over the reactor inlet cross section as a NH_3-air mixture (5% ammonia in air) before the SCR reactor by a fine nozzle grid (several thousand nozzles) or by actuator discs. The NH_3 throughput through the nozzles can be controlled using control valves to achieve an even distribution over the reactor cross section. The distribution of the ammonia in the flue gas is checked by a NO_x measurement grid every 2 years and the nozzles adjusted if necessary. At the same time the catalyst activity is also checked. A catalyst block is removed from predefined locations in the reactor with the block shut down and tested for chemical activity in the catalyst supplier's test apparatus . The catalysts are also checked visually in the first cat layer with the block shut down. If the catalyst is blocked or clogged by ash, the ash is removed with an industrial vacuum cleaner system.

The power station owners/operator can also check for catalyst activity. Experience has shown that about 90% of the NH_3 slip in the flue gas after the SCR reactor is absorbed by the fly ash or is introduced into the fly ash by reaction of NH_3 with the flue gas SO_3. Since the quality of the fly ash (certified for disposal in the cement industry) is checked at the power station about every 2 days, the NH_3 content of the fly ash is also checked there. For use in the cement industry, the NH_3 content of the ashes should not exceed 100 ppm. Normally this value is about 50 ppm, and the catalyst volume (depending on the ash content of the coal) is designed so that a NH_3 slip is only 1 to 2 ppm. A significant increase in the NH_3 content of the ash indicates that the catalyst is losing its activity and a catalyst layer needs to be changed during the next scheduled shutdown of the SCR.

In Germany the ammonia required for the SCR reaction is usually stored in liquid-NH_3 tanks at the power station. These liquid tanks were built underground or as double-walled tanks for safety reasons. The NH_3 is usually delivered in railway tankers. The ammonia for new plants is usually stored as 40% ammonia water in stainless steel tanks, as these are not subject to strict safety conditions. A disadvantage is, however, the specific higher price of the ammonia in water in comparison with liquid ammonia.
The EU'S large combustion plant directive (LCPD) requires a NO_x emission value of 200 mg/m³ for a new plant. This value can be achieved in a lignite power station by combustion modifications alone. This is equally applicable to Greek lignite as German. In a hard coal power station this NO_x limit cannot be achieved by furnace technical measures so a $DeNO_x$ catalyst plant is required there.

A preliminary study of the necessary catalyst volume for an SCR plant for a new Greek coal power station with the specific Russian and South African coals has been performed.
The power station size (300 MW_{el}) is consistent with the size used in the FGD study above, i.e.

Unit size: 300 MW_{el}
Flue gas volume flow: 950,000 m³/h STP, wet
NO_x content in raw gas: 700 mg/m³ STP, dry
NO_x content in pure gas (EU standard): 200 mg/m³ STP, dry
NO_x separation factor: 71%
Catalyst type: honeycomb, 7.3 mm pitch, surface 420 m²/m³
Catalyst activity: K = 35 m/h at approx. 370°C

Result: Catalyst volume: 300 m³, at 1 – 2 ppm NH₃ slip
Ammonia consumption: 0.19 t/h

8. Economic Aspects

For retrofitting NO_x reduction measures, it is not possible to use specific investment costs as for new power plant. The modifications, e.g. firing system, have to be developed for each plant individually taking into account the existing design and the characteristics of the lignite or hard coal.

Prices for the necessary investment in reducing emissions have to be obtained from the market place for individual plants.

To determine the commercial status of a retrofit the following facts should be obtained:

- The price for modifications of the firing system, by qualified proposals from suppliers.
- The knowledge about the expected remaining life time of the unit.
- The forecast of generation for the remaining life time of the unit
- Expected maintenance budget for the remaining life time

With these facts and assumptions, the economics can be reviewed and the generation cost determined for the particular unit.

8.1. References

[1] Bonekamp, B.; Lambertz, J.; Pflugbeil, M. et al.: 1000 MW BoA Niederaußem, Energiewirtschaftliche Tagesfragen 52 (2002), no. 9, special BoA edition, pp. 1-12.

[2] Lambertz, J.; Tippkötter, T.: Die Entwicklung der Kraftwerkstechnik im rheinischen Revier zum Braunkohlenkraftwerk mit optimierter Anlagentechnik. Bergbau 52 (2001), no. 8, pp. 343-348.

[3] Böcker, D., Klöcker, K.-J., und Klutz, H.-J.: The WTA Process – A New Drying Process for Brown Coal. Braunkohle 41 (1989), no. 5, pp. 169-172.

[4] Klutz, H.-J, Klöcker, K.-J, Lambertz, J.: Die Rheinbraun-WTA-Technik – Entwicklung und erste Betriebsergebnisse. Braunkohle 46 (1994), no. 6, pp. 4-11.

[5] Klutz, H.-J, Klöcker, K.-J, Lambertz, J.: The WTA Process as a Pre-Drying Stage for Modern Lignite-Based Power Plant Concepts. VGB Kraftwerkstechnik 76 (1996), no. 3, pp. 224-229.

[6] Klutz, H.-J., Ewers, J: Entwicklung der WTA-Feinkorntrocknung. VDI Berichte, no. 1495, 1999, pp. 259-271.

[7] Götte, C., Pollack, M., Heitmüller, R. J., Müller, H., Scheffknecht, G.: Untersuchung des Verschlackungsverhaltens der Brennkammer von trockenbraunkohlegefeuerten Dampferzeugern, "Verbrennung und Feuerungen", 19. Deutscher Flammentag,

[8] File US 031- Funnel reconstruction in the Neurath power plant A/B units
            Decision confirmed by computer simulations
            (8 Seiten) Neurath

[9] File US 130706 - Corroboration of boiler reconstruction measures by 370
                computer
                (5 Seiten) Neurath

[10] Final Manuscript - Development trends for simulation

[11] Paper ID 348 - Based optimisation of boiler operation at EnBW, Power Gen Europe

[12] Corroboration of boiler reconstruction measures by 3 D Computer Simulation
     Dr. Ing. Risio, Dipl. Ing. N. Plassmann, Dipl. Ing. F. Wissel,
     Dipl. Ing. Egbert Reinartz

[13] Conversion of lignite Firing Systems in Neurath Power Station, operating experience with RS Jet burners
     Passman, Reinartz, Dr. Tigges VGB Power Tech

[14] Furnace reconstruction in the Neurath power Plant A/B Units
     Decision confirmed by computer simulation
     Reinartz, Passmann, Dr. Risio

[15] Khan I; Cahill P; Matts D; "Clean Coal Technologies Overview" RWE Power International report, TECH/JJB/657/06.

[16] Lanfanechere 1, Basu,P, Jestin L, J of Institute of Energy, 68 (477), 184-192, 1995

[17] Kakaras E, Grammelis P, Skodgras G and Vourliotis P, Thermal Science vol 7, No2, 33-42, 2003