

**CO-FIRING OF BIOMASS, COAL WASTE AND COAL IN MINING SITES
FOR ELECTRICITY GENERATION
(COBIOCOWA)**

*Javier Alonso Martínez, María Martín Egido
Luis Gutiérrez Galiano
Andree Faaij, Carlo Hamelinck
Javier Ballester, Ramón Ichaso
Herminio Sastre, Manuel Mahamud*

**UNIÓN FENOSA INGENIERÍA S.A. (UFISA) (CO-ORDINATOR)
UNIÓN ELÉCTRICA FENOSA
UTRECHT UNIVERSITY
UNIVERSIDAD DE ZARAGOZA
UNIVERSIDAD DE OVIEDO**

CONTRACT JOR3-CT98-0276

**I
PUBLISHABLE FINAL REPORT**

May 1998 To December 2001

Research funded in part by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III

Table of contents

1	ABSTRACT	5
2.	PARTNERSHIP.....	7
3	OBJECTIVES OF THE PROJECT.....	7
4	TECHNICAL DESCRIPTION	8
4.1	ASSESSMENT & CHARACTERIZATION OF RESOURCE BASE	8
4.1.1	<i>Introduction.....</i>	8
4.1.2	<i>Inventory.....</i>	8
4.1.2.1	Synthesis of the inventory.	9
4.1.3	<i>Methodology.....</i>	10
4.1.4	<i>Results Of Analysis.....</i>	10
4.1.4.1	Results for biomass	10
4.1.4.2	Results for coals.....	12
4.2	REVIEW OF THE STATE OF ART	13
4.2.1	<i>Introduction.....</i>	13
4.2.2	<i>Previous studies and projects.....</i>	15
4.2.2.1	Introduction	15
4.2.2.2	Maasvlakte station co-firing pellets (NL).....	15
4.2.2.3	Hemweg unit 8 co-firing sewage sludge (NL).....	17
4.2.2.4	EPON co-firing demolition wood (NL).....	19
4.2.2.5	Vestkaft Unit 1 co-firing wood (DK).....	22
4.2.2.6	St. Andrä station retrofit with grate (A)	24
4.2.2.7	Zeltweg station with external gasifier (A)	26
4.2.2.8	Amer power with external gasifier (NL)	27
4.2.3	<i>Routes.....</i>	29
4.2.3.1	Route: Direct combustion	30
4.2.3.2	Route: Drying, pulverising and existing burners	35
4.2.3.3	Route: Drying, pulverising and separate burners.....	36
4.2.3.4	Route: Drying and pelletising.....	37
4.2.3.5	Route: Separate pyrolysing	37
4.2.3.6	Route: Separate gasification.....	38
4.2.3.7	Route: Retrofit to integrated co-combustion grate.....	40
4.2.3.8	Route: Retrofit to bubbling fluidised bed boiler	41
4.2.3.9	Route: Retrofit to CFB boiler.....	42
4.2.3.10	Route: Separate combustion unit	44
4.2.4	<i>Conclusions</i>	45
4.2.5	<i>References</i>	49
	<i>Annex A Drying technologies.....</i>	52
4.3	MODELLING & TESTING.....	61
4.3.1	<i>Modelling.....</i>	61

4.3.1.1 Colophon.....	61
4.3.1.2 Abstract.....	61
4.3.1.3 Introduction	62
4.3.1.4 The Aspen Plus simulation program	64
4.3.1.5 The fuel.....	65
4.3.1.6 Size reduction	67
4.3.1.7 Drying.....	69
4.3.1.8 Fireplace.....	70
4.3.1.9 Steam cycle	73
4.3.1.10 Researched cases.....	74
4.3.1.11 Conclusion.....	77
4.3.1.12 Literature	78
Aspen Plus model flowsheet	80
4.3.2 <i>Lab scale test and test in a semi-industrial furnace</i>	82
4.3.2.1 Background and motivation.....	82
4.3.2.2 Methodology employed.....	82
4.3.2.3 Results obtained and key findings of the work	83
4.3.2.3.1 Lab-scale tests.....	84
4.3.2.3.2 Semi-industrial tests.....	86
4.3.2.3.3 Analysis of the implementation in Narcea-I.....	89
4.4 TECHNOLOGICAL DATA BASE SET-UP	92
4.4.1 <i>Description of the data base</i>	92
4.4.2 <i>Conclusions</i>	97
4.5 TECHNICAL FEASIBILITY OF COFIRING IMPLEMENTATION.....	98
4.5.1 <i>Analysis of the different options considered</i>	98
4.5.2 <i>Reburning option</i>	98
4.5.2.1 Detail modifications to carry out.....	98
4.5.2.1.1 Lorry reception area.....	98
4.5.2.1.2 Biomass transport to the storage area	98
4.5.2.1.3 Biomass storage area	98
4.5.2.1.4 Biomass transport to the feeding system.....	99
4.5.2.1.5 Biomass injection.....	99
4.5.2.1.6 Overfire air injection.....	99
4.5.2.1.7 Gas treatment equipment	99
4.5.2.2 Restrictions to take into account	99
4.5.2.3 Operational problems to overcame	100
4.5.2.4 Environmental impact	100
4.5.2.4.1 Atmospheric impact	100
4.5.2.4.2 Liquid and solid wastes	100
4.5.3 <i>Conclusions</i>	100
4.6 ECONOMIC ASSESSMENT.....	102
4.6.1 <i>Estimated investment costs</i>	102
4.6.1.1 Land required	103
4.6.1.2 Civil works	103
4.6.1.3 Biomass storage area	103
4.6.1.4 Biomass transport equipment	103

4.6.1.5 Feeding equipment	103
4.6.1.6 Gas treatment equipment	103
4.6.1.7 Instrumentation & control.....	103
4.6.1.8 Installation costs.....	104
4.6.1.9 Engineering project.....	104
4.6.1.10 Building contractor	104
4.6.1.11 Unforeseen expenses.....	104
4.6.2 <i>Operational and maintenance costs</i>	105
4.6.2.1 Total input costs.....	105
4.6.2.2 Transporting cost	105
4.6.2.3 Maintenance and reparation cost	105
4.6.2.4 Total labour	105
4.6.2.5 Private security.....	106
4.6.2.6 Management	106
4.6.2.7 Insurance	106
4.6.2.8 Environmental cost.....	106
4.6.2.9 Rent of equipment	106
4.6.2.10 Various	106
4.6.3 <i>Incomes</i>	107
4.6.3.1 Electricity production.....	107
4.6.4 <i>Analysis of the cash-flow</i>	107
4.6.5 <i>Conclusions</i>	109
5. RESULTS AND CONCLUSIONS	110
5.1 RESULTS.....	110
5.1.1 <i>Availability of biomass and high ash coals in the Narcea Power Plant area</i>	110
5.1.2 <i>Procedures for the Determination of Heating Values of High Ash Content Coals</i>	110
5.1.3 <i>Report Biomass pre-treatment and co-firing technologies</i>	110
5.1.4 <i>Report: Modelling of the Narcea power plant for evaluating the impacts of various co-combustion schemes on plant performance and emissions</i>	111
5.1.5 <i>Aspen Plus Computer model for cofiring in pulverised fuel boiler</i>	111
5.1.6 <i>Database on biomass combustion</i>	111
5.1.7 <i>Database on biomass/coal cofiring</i>	111
5.1.8 <i>Technological data-base</i>	112
5.1.9 <i>Analysis of technological modifications</i>	112
5.2 CONCLUSIONS	113
6 EXPLOITATION PLANS AND ANTICIPATED BENEFITS	115
7 PHOTOGRAPH, DIAGRAM OR FIGURE TO ILLUSTRATE POTENTIAL APPLICATIONS OF THE PROJECT	116

1 Abstract

The present project has covered the different aspects required to implement the best technology for co-firing of biomass (mostly forestry and sawdust residues) with coal and coal waste in Narcea I, power plant and to determine the overall feasibility.

Initially it has been carried out an estimation of biomass waste in the Tineo area (Spain), where the plant is located, not only the amount produced in sawmills, but also all wastes left in the woodland as a result of forestry activities.

According to the assessment carried out, the use of coal residues is not possible from an economic point of view, and is also environmentally unacceptable. Due to this circumstance, it was studied other coal-based products such as high-ash coals or coal from the mine without any kind of pretreatment, and consequently with less additional costs. Information about gross coal production and production foresees were obtained from the mining companies in the area.

Afterwards it has been collected representative biomass and coal samples for carrying out the analysis. These analysis have consisted of proximate analysis, ultimate analysis, particle size distributions and determination of the heating value, that were carried out according with standard accepted procedures (ISO standards when applicable).

Simultaneously it has been performed a review of the state of art which has allowed to identify the advances and operational problems in relation to pretreatment, energy generation and waste production.

Once it has been identified the most promising technological solutions for Narcea I, it has been modelled the overall process with Aspen Plus in order to predict the behaviour of the plant with the changes suggested.

Considering the results obtained in the modelling stage it has been designed the testing stage, which can be divided in:

- Lab scale tests: led to the determination of the “universal” kinetic parameters for different types of coal and biomass and the determination of the “high-temperature volatile yield”.

The main conclusion of this stage is that the high-ash coal and standard coal have similar kinetic parameters. Therefore the high-ash coal do not offer any possible advantage to the overall process because it does not improve the kinetic aspect and it worsens the thermodynamic and environmental aspects (lower LHV and higher ash production than standard coal).

- Semi-industrial tests: two different strategies has been considered, combustion of coal/biomass blends and separation injection of

biomass. It has not been considered to introduce high-ash coal or coal from mine without any kind of pretreatment

According to the results obtained, the oak wood has been selected as the biomass fuel, in the proportion of 20% of total thermal input and the reburning technique has been selected as the best one considering the geometry of the Narcea I furnace (arch-fired).

Based on the results of the activities previously mentioned and in the engineering experience of different companies, it has been described in detail the technological modifications required to shift coal combustion to co-firing and the technoeconomic feasibility of these modifications.

Afterwards it has been studied the economical feasibility of the project. To determine this feasibility it has been considered not only the modifications (because the avoided costs will not possibly compensate the investment required) but the overall economical situation of the plant.

After performing the economic analysis of the feasibility of the modifications, it has been concluded that the modifications are not economically feasible because the incomes associated to the electricity selling can not compensate the investment required and the operational and maintenance costs. Additional benefits in relation to NO_x reduction are not valuable, due to the fact that no regulation applies to set incomes/cost reduction about this environmental effect.

If the regulation applicable, the remaining life of the plant and the market conditions are modified, the economic feasibility of the proposed modifications will be affected. The modifications could become economically feasible.

2. Partnership

Partner	Contact person	Adress	Telephone
Unión Fenosa Ingeniería (UFISA)	Javier Alonso Martínez	C/ Piquer 7, 28033 Madrid Spain	34-91- 3847100
Unión Eléctrica Fenosa C.T. Narcea	Luis Gutiérrez Galiano	Soto de la Barca (Tineo) 33876 Asturias Spain	34-98- 5800957
Utrecht University Faculty of Chemistry Dept. Science, Technology and Society	Andree Faaij	Padualaan 14, 3584 CH - Utrecht The Netherlands	31-30- 2537601
Universidad de Zaragoza Fundación Empresa Area Mec. De Fluidos Centro Politec. Superior	Javier Ballester	C/ María de Luna 3, E-50015 - Zaragoza Spain	34-976- 762153
Universidad de Oviedo Facultad de Química Dept. Ing. Química y Tec. Del M. Ambiente	Herminio Sastre	Avda. Julian Clavería 8, 33701 Oviedo Spain	34-976- 5103437

3 Objectives of the project

The objective of this project is to carry out a study to determine the possibilities of co-firing of biomass (mostly forestry and sawdust residues) with coal and coal waste from mining sites in Narcea I, 65 Mwe coal fulled plant sited in Tineo (Asturias – Spain). The main relevance of the project is to increase sharing of renewables in the energy system, to reduce fossil fuel use and to reduce environmental impact while at the same time using local resources with major benefits for the local economy.

4 Technical description

4.1 Assessment & characterization of resource base

4.1.1 Introduction

In this report is summarized the work carried out by the research team of the University of OVIEDO (Department of Chemical and Environmental Engineering) concerning the characterization of biomass fuels as well as coals of high ash content.

The characterization of fuels includes: proximate analysis, ultimate analysis, heating values, granulometric determinations and additional drying curves. Location of sawmills and determination of type and amount of wastes produced were also carried out and a rough inventory of wood processing industries is included in this report. As it was suggested by Utrecht in an intermediate meeting, the content of chlorine and heavy metals (Pb, Hg and Cg) in coal samples was measured. Determinations of the sulphur and chlorine content of wood samples were as well carried out.

The high ash content and the dispersion of coal waste landfills lead UFISA to ask OVIEDO the collection of samples of high-ash content coals from the mining industries nearby. It was also found of interest to get information concerning future productions of the mining sites.

The collection of samples and their characterization was carried out. The results of the analysis of coal and biomass samples, actual productions of wood residues and foreseeable productions of the mines are collected in this report.

4.1.2 Inventory

In the first stages of the project there was a lack of concrete data regarding production and availability of biomass waste (wood residues). According to the scheduled timetable it was necessary to know where the collection of biomass samples should be carried out. Consequently, UFISA asked OVIEDO to carry out a rough survey of the sawmills located in the vicinity of Narcea Power Station. The starting information to carry out this task was supplied mainly by the chef chemist of Narcea Power Station and some others by SADEI (Sociedad Asturiana de estudios Económicos e Industriales).

However, it should be pointed out that for the correct estimation of biomass waste, not only should be considered the amount produced in sawmills, but also all wastes left in the woodland as a result of forestry activities. The latter is very difficult to calculate, so a determined percentage of total wood production in this zone can be considered as an approach. It is also necessary to bear in mind that not all the wood produced is processed in the vicinity.

4.1.2.1 Synthesis of the inventory.

Twenty one producers of wood residues located near the Narcea Power Station were interviewed in order to obtain data regarding production, destination, wood type and price of the residues. The following table summarises the wood processing industries existing in the Council of Tineo and in the closest Councils. More detailed information concerning types of wood, kind of wood wastes, amount of waste production and fate and price of residues is found in the Appendix of the Report submitted in July 1999.

Sites of sampling

The selection of sawmills to obtain samples for testing was carried out by taking into account the following parameters:

- distance to Narcea Power Station.
- amount of production.

- different types of products.

Three sawmills were chosen.

Samples of pine sawdust as well as additional samples of eucalyptus, chestnut tree and oak tree sawdust coming from the zone, were supplied by the chef chemist of Narcea.

The use of coal residues may not be possible from an economic point of view, and is also environmentally unacceptable. Due to this circumstance, the selection of other coal-based products as high-ash coals or coal from the mine without any kind of pretreatment, were selected for analysis. Information about gross coal production and production foresees were obtained from the mining companies by phone contact and direct interviews.

Afterwards, sampling was carried out where it was possible (three mines).

4.1.3 Methodology

For biomass sampling (sawdust and firewood) and mainly for coal sampling, which is a material with a very heterogeneous nature, obtaining a representative sample is a complex and delicate task. Sampling was carried out carefully in order to guarantee that determinations correspond with the properties of the whole volume.

Proximate analysis, ultimate analysis, particle size distribution and determination of the heating value, were carried out according with standard accepted procedures (ISO standards when applicable).

4.1.4 Results Of Analysis

4.1.4.1 Results for biomass

Eleven samples of wood were analysed. They came from three different sites and correspond to eucalyptus, oak, pine and chestnut wood.

The determinations carried out were: proximate and ultimate analysis, heating values, and particle size analysis. Low heating values of wet samples ranged in the interval 8-10,5 kJ·g⁻¹ depending mostly of the water content of the samples. Consequently, for this type of products, the moisture content is critical for the energetic valorisation. Given the fact that the degree of water content of wood residues may be highly variable depending - among others - on the type of wood, time of storage, weather conditions and peculiarities of the different wood processing plants, it was found useful to correlate for the different samples, the LHV as a function of the moisture content.

In addition, biomass drying curves were obtained for the different samples.

4.1.4.2 Results for coals.

The determinations carried out were: proximate and ultimate analysis, heating values, particle size analysis, heavy metals and chlorine.

The similar values for LHV in dry ash-free basis, indicate that the basic characteristics of the analysed coals are quite similar. This is not surprising taking account that the three coals correspond to the anthracitic class according to the ASTM classification of coals by rank.

In the case of coals, the variation of moisture is not to be expected as wide as for the biomass but the correlations of LHV and moisture of samples were obtained as well.

Lower heating values ranged in the interval $14\text{-}22 \text{ kJ}\cdot\text{g}^{-1}$ depending of the moisture and the ash content of the coals.

Drying curves where obtained under the same conditions mentioned for the biomass.

The content of heavy metals is always under 1000 ppm for Hg under 140 ppm for Cd and under 20 ppb for Pb.

4.2 Review of the state of art

4.2.1 Introduction

In this report a review is given of the state-of-the-art in co-firing coal, biomass and coal waste. Furthermore this report will have the objective to determine the routes in which the biomass can be co-fired in the Narcea I unit.

It will assess previous studies and projects carried out, identifying advances and operational problems so far in relation to three parts of the application: pre-treatment, energy generation and waste production. For pre-treatment an assessment of previous studies is made for the drying, sizing, screening and store of biomass as well as final mix with mine waste and/or coal. For energy generation the behaviour and consequences of combustion are studied, including efficiency and ranges of share of fuels mixtures (in relation to composition and combustion behaviour). Thirdly, waste production will be studied in which characterisation of ashes and emissions including heavy metals and levels of NO_x, SO₂, and particles.

After the assessment of the previous studies an overview is given of the possible routes to co-fire biomass in the Narcea I unit.

In the second chapter of this report the previous studies and projects will be assessed in separate sections. In chapter 3 an assessment is made for the most suitable technological solution for the Narcea I unit and solutions are given to overcome operational problems.

4.2.2 Previous studies and projects

4.2.2.1 Introduction

In this chapter previous studies and projects will be assessed in separate sections. **Error! Unknown switch argument.** gives specific projects of cofiring pulverised coal with biomass. Since Union Fenosa has reported about experiences of cofiring biomass in power plants in USA [González et al., 1998], this report concentrates on projects outside USA. The projects discussed in this report are given in bold in **Error! Unknown switch argument..**

Table Error! Unknown switch argument. Examples of coal/biomass cofiring projects

Plant	Fuel	Size (MW _e)	Technology
EPON Centrale Gelderland (NL)	Coal/demolition wood	602	Pulverised coal
GPU Genco Shawville station (USA)	Coal/waste wood	130	Pulverised coal
Iowa Electric Light & Power Sixth Street Station (USA)	Coal/agricultural refuse	6-15	Pulverised coal
Tennessee Valley Authority, Kingston Station (USA)	Coal, waste wood	150	Pulverised coal
Uppsala Energi AB (S)	Coal (peat)/wood chips	200	Pulverised coal
Zeltweg station (A)	Coal/bark	137	Gasifier bark/pulverised coal
Kymijärvi station (Fin)	Coal/wood/plastic s/ paper/cardboard	167	Gasifier/pulverised coal
St. Andrä station (A)	Coal/bark	124	Pulverised coal/grate
Amer Station (NL)	Coal/demolition wood	600	Gasifier wood/pulverised coal
Maasvlakte Station (NL)	Coal/biomass pellets	540	Pulverised coal
Hemweg Station (NL)	Coal/sewage sludge	630	Pulverised coal
Vestkaft station (DK)	Coal/demolition wood	125	Pulverised coal

This report will assess previous studies and projects carried out, identifying advances and operational problems so far in relation to three parts of the application: pre-treatment, energy generation and waste production.

4.2.2.2 Maasvlakte station co-firing pellets (NL)

Description project

In the Maasvlakte coal-fired power station in The Netherlands a project is started to co-combust 5% sewage sludge, de-inking sludge and compost residues.

The Maasvlakte Power Station was commissioned in June 1975 and were at that time fired by natural gas/oil. The station was converted into burning coal in 1988. The station consists of two units, each with a capacity of 540 MW_e by firing 180 ton coal per hour per boiler. The boiler has a steam production of 1600 tons per hour with a pressure of 183 bar by 540°C main steam temperature and 540°C-reheat steam temperature. The flue gas cleaning systems exists of an electrostatic fly-ash filter and a desulphurisation installation.

Pre-treatment

The biomass streams co-combusted in the Maasvlakte power station are sewage sludge, de-inking sludge and compost residues.

The wet sewage sludge has a dry matter content of 20%_{d.m.} and is thermally dried with natural gas to a dry matter content of 90%_{d.m.}. In this way it is possible to reduce the volume and weight by a factor 4. This dried sewage sludge has a lower heating value of 10 MJ/kg and an ash content of 35%.

The de-inking sludge is a residue of the paper industry. It arise from the recycling process of paper and consist manly of short fibres and ink. A deinking process removes the ink. After this process the sludge has a dry matter content of approximately 50%.

The compost residues arise from the composting process of prunings. These pruning is a woody stream released during the maintenance of example public parks. It mainly consists of wood, partly leaves and some other waste. After the composting process the tradable compost is separate from the coarse material, mainly wood. This coarse material is used for co-combustion.

Nowadays these biomass streams are transported from the east to the south of The Netherlands by truck. In the future is will be transported by ship. The streams are transported by a tunnel conveyer belt from the ship to a separated pre-treatment plant in the surrounding of the power plant. In this pre-treatment plant the biomass streams are mixed and pelletised to homogenous pellets, with moisture content of 50%. An open conveyer belt transports these pellets to the coal plant. Halfway through the coals are added to the conveyer belt. In the coal plant the mixture of pellets and coal are milled and partly dried into one of the five coal mills. This drying takes place by heated primary air of the fans in these coal mills.

Energy generation

The power station has a net capacity of 520 MW_e, with an own operation capacity of 22 MW_e. The efficiency of the station at full load is 40.6%. During the experiment no decrease of the electrical efficiency could be found.

Waste production.

To fulfill the Dutch Emission Standards for boilers of electricity production facilities (BEES-A), the Maasvlakte Power Station utilised with an electrostatic fly-ash filter and a desulphurisation installation. The emission figures for co-combustion of the pellets are not public at this moment.

Remark

According to the latest information the moisture content of 50% of the pellets has too much influence on the process. The drying capacity of the primary air into the mill is too low to dry the pellets. To dry the pellets the heat input into the mill has to be increased. As a consequence of this the flue gas quantity was too high to guarantee the gas cleaning in the electrostatic fly-ash filter and a desulphurisation installation. To overcome these problems the pellets have to be dried before entering the coal mill [Kromhout, 1998].

4.2.2.3 Hemweg unit 8 co-firing sewage sludge (NL)

Description project

Unit 8 of the Hemweg power station is selected to execute large-scale tests to co-combust sewage sludge. This unit was commissioned in June 1994 and has a net output of 630 MW_e by firing coal. The boiler of this unit has a steam production of 2000 tons per hour with a pressure of 260 bar by 540°C main steam temperature and 568°C-reheat steam temperature. The flue gas cleaning systems exists of an electrostatic fly-ash filter and a desulphurisation installation. The goal for these full scale experiments were gaining the first indication of the technical feasibility of sewage sludge co-combustion and measuring the environmental impact of sewage sludge co-combustion [Dijkman et al., 1995].

Pre-treatment

In the past wet sewage sludge (20%_{d.m.}) of sewage treatment plants in Amsterdam were sent to deposits, but increasing deposition rates force the reduction of sludge amounts. Therefore, the sludge was thermally dried with natural gas to a dry matter content of 90%_{d.m.}. In this way it is possible to reduce the volume and weight by a factor 4. This dried sewage sludge has a lower heating value of 10 MJ/kg and an ash content of 35%.

The output of the drying systems of the sewage treatment plant is compressed to briquettes to overcome dust and smelling problems. These briquettes are mechanically weak and will easily disintegrate into fine dust during storage, compacting and transport to the power plant.

To store the dried sewage sludge a small bunker is built (especially built for dosing secondary materials). During this storage the dried sewage sludge started to heat spontaneously. Compacting the sludge by a shovel lowered the temperature (minimising the trapped oxygen).

The content of this bunker is dumped on a coal carrying conveyor belt and this mixture is transported to the coal mills. The handling of the briquettes is a problem if you have to mix it with the coal flow in proper conditions.

During the experiments no mechanical wear of the coal mills could be found [Dijkman et al., 1995].

Energy generation

During the full-scale experiments no significant increase of slagging could be found during the visual inspections.

During the experiment no decrease of the electrical efficiency could be found. So co-combust sewage sludge into the Hemweg 8 unit utilise 43% of its energy content [Dijkman et al., 1995].

Waste production.

The waste production can be divided into three categories: emissions depending on the combustion characteristics, emission depending on the input and solid waste.

The compounds of which the concentration in flue gas mainly depends on the combustion characteristics are for example CO, C_xH_y, dioxin and partly NO_x. The CO concentration in flue gasses shows large fluctuations, which were caused by adjustments of the burners and no relation between CO and co-combustion of the sludge. During the experiments it was not possible to determine a significant increase in C_xH_y and dioxin emissions. The co-combustion of sewage sludge didn't show an increase in NO_x, although the sludge has a nitrogen content then coal. Probably the nitrogen is volatised during the early stage of combustion and the formed NO_x is reduced during the last stage of combustion [Gast et. al., 1995].

The compounds of which the concentration in flue gas mainly depends on the input are for example sulphur, heavy metals, HCl, HF.

The uncleaned flue gas shows an increase in sulphur concentration caused by the high concentration in the sludge. Fortunately the scrubber removes 90% of the SO₂.

An increase in the concentration of volatile heavy metals (like cadmium and arsine) in the flue gas by co-combustion of sewage sludge wasn't determined. The element mercury caused an increase in emission, but remains still below the legislative limit.

To fulfil the Dutch emission standards for boilers of electricity production facilities (BEES-A), the Hemweg 8 unit is utilised with an electrostatic fly-ash filter and a desulphurisation installation.

The heavy ash particles are trapped in the boiler and removed as bottom ash. This ash is directly usable for road filling and as raw material in the building industry. Because sewage sludge has another composition then coal, it is possible that the composition of the bottom ash is influenced. According to analyses executed with bottom ash samples there is an increase in the cadmium, copper, lead and zinc concentration by co-combustion of sewage sludge. This increase of heavy metals in the bottom ash didn't show increase in the leachability of heavy metals [Gast et al., 1995].

All the remainder fly ash particulates are practically trapped by the electrostatic filter. This fly ash is utilised in cement manufacturing, road building or in the stone industry. When sewage sludge is co-combusted it is clear that there is an increase in heavy metal concentration, but leachability experiments didn't show an increase in leachability.

In the desulphurisation installation a fine mist of a mixture of lime and water removes 88% of the SO₂, by the formation gypsum. Besides removing of the SO₂, the desulphurisation installation is able to reduce the content of fly ash, chlorine en fluorine in the flue gasses.

4.2.2.4 EPON co-firing demolition wood (NL)

Description project

The Dutch electricity production company EPON has started in 1994 the construction of facilities which enable 4.5% co-combustion with (demolition) wood chips at their powder coal fired 600 MW_e power plant in Nijmegen. The pre-treatment of the wood chips consists of ferro/non-ferro separation, sieving, milling and drying. The wood chips are milled to a size of 1.5 mm and dried with spent steam. The drier is able to dry wood with a moisture content of 20% down to a moisture content of 8%. [Broek et al., 1995].

Pre-treatment

Waste wood and demolition wood are assembled at three locations in the Netherlands. At these locations the wood is sorted and processed to raw wood chips and transported into containers to the power station. The 27 containers are placed on an automated traverse and dumping system. After ferro/non-ferro separation and windsifting two hammer mills reduce the material from 3 cm to particles of max. 4 mm. After that, the material is transported to four pulverisers of the installation where it is further reduced and dried with pre-heated air [EPON, 1995]. The wood powder has a moisture content of <8% [Pennink, 1996].

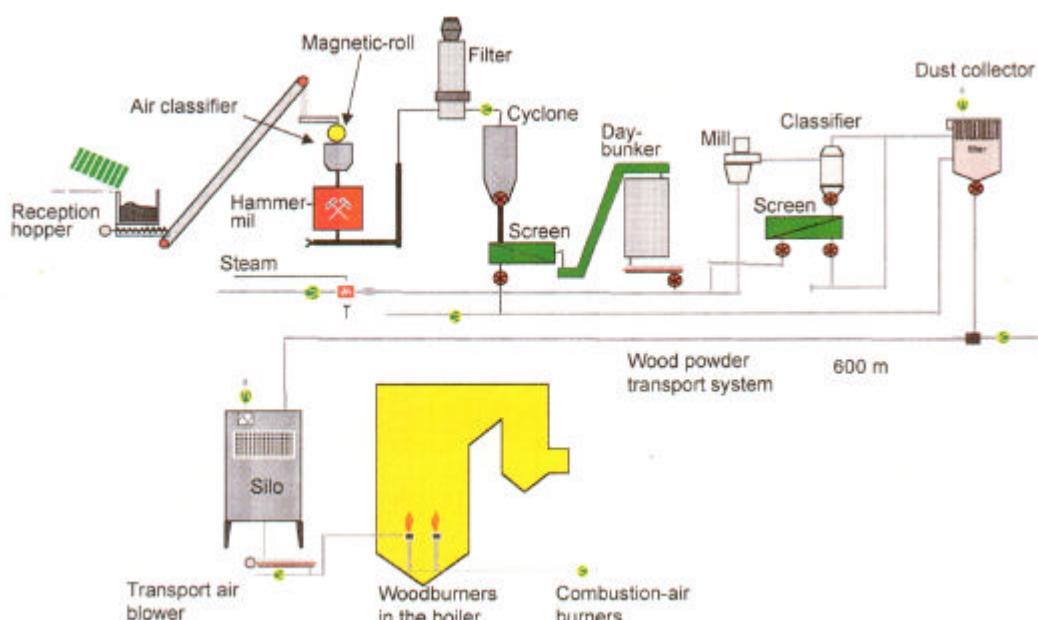


Figure Error! Unknown switch argument. Process scheme wood installation [EPON, 1995]

Energy generation

Because of the differences in size between the coal (75 µm) and wood particles (1.5 mm) it seems not possible to burn the two streams into the same burners [Pennink, 1996]. Therefore special wood burners with a total capacity of 54 MW_{th} are mounted in the sidewalls of the boiler (two on each side). These wood

burners are able to add the wood with 2.8 kg/s. The net electric efficiency is 37%_{LHV}

Waste production

The wood chips used in this project have a moisture content of <20% and a calorific value of >16 MJ/kg. The lead, zinc and chlorine concentration of this material are respectively <1500 µg/g, <1400 µg/g and <400 µg/g [Penniks, 1996].

The emission figures of the co-combustion of waste wood into the Centrale Gelderland did not show an increment of the emissions. There are no flue gas analyses available of the experiments with the co-combustion of waste wood. Therefor, figures are taken from pilot tests executed by the KEMA. In 1995 flue gas analyses are executed of combustion of coal and fine waste wood in a 1 MW_e pilot test facility of KEMA Environmental Technology. According to these tests the concentration of cadmium, lead and zinc in flue gas will increase if fine waste wood is co-combusted. The SO₂ concentration in the flue gas will not increase if fine waste wood is co-combusted compared to coal only. **Error!** **Unknown switch argument.** gives an overview of the flue gas analyses of the mentioned pilot tests.

Table Error! Unknown switch argument. Flue gas analysis of combustion of coal and fine waste wood in a 1 MW_e pilot test facility of KEMA [Beekes, 1995]

	100 % coal	coal/wood (95/5)	coal/wood (90/10)	coal/wood (85/15)
Cadmium ¹ ($\mu\text{m}/\text{m}^3$)	1.3	1.39	2.3	6.5
Lead ² ($\mu\text{m}/\text{m}^3$)	9.1	32.8	37.9	66.1
Zinc ³ ($\mu\text{m}/\text{m}^3$)	26	58	66	105
Mercury ⁴ ($\mu\text{m}/\text{m}^3$)	17.5	3.1	<2.6	<3
Dust (mg/m ³)	129	79.9	83	121
O ₂ (V%)	5	4.7	5.1	5.2
CO ₂ (V%)	13.2	14.3	13.9	13.9
CO (ppm)	34	226	151	145
C _x H _y (ppm)	<1	9	4	5
NO _x (ppm)	251	170	293	189
SO ₂ (ppm)	531	529	533	513

The ash content of wood is ten times less than that of coal. Consequently, the production of fly ash will be reduced by 4 kton by co-combustion of 4.5% waste wood [Penninks, 1996].

According to the pilot tests of KEMA co-combustion of waste wood the concentrations of cadmium lead and zinc in fly-ash samples show an increase of these heavy metals. **Error! Unknown switch argument.** gives the concentrations of cadmium, lead and zinc in fly-ash samples of combustion of coal and fine waste wood in a 1 MW_e pilot test facility of KEMA.

Table Error! Unknown switch argument. Concentrations of cadmium, lead and zinc in fly-ash samples of combustion of coal and fine waste wood in a 1 MW_e pilot test facility of KEMA [Beekes, 1995]

	100 % coal	coal/wood (95/5)	coal/wood (90/10)	coal/wood (85/15)
Cadmium (mg/kg)	1.8	3.0	4.0	5.0
Lead (mg/kg)	200	700	1300	2000
Zinc (mg/kg)	300	800	1500	2100

¹ Cadmium concentration waste wood and coal are respectively 2.3 and 0.09 $\mu\text{g/g}$

² Lead concentration waste wood and coal are respectively 817 and 3.05 $\mu\text{g/g}$

³ Zinc concentration waste wood and coal are respectively 1235 and 12 $\mu\text{g/g}$

⁴ Mercury concentration waste wood and coal are respectively 0.05 and 0.03 $\mu\text{g/g}$

Table Error! Unknown switch argument. Leachability of heavy metals from fly-ash of combustion of coal and fine waste wood in a 1 MW_e pilot test facility of KEMA [Beeckes, 1995]

(mg/kg)	100 % coal	coal/wood (95%/5%)	coal/wood (85%/15%)
As	0.04	0.03	0.08
Cd	0.002	<0.001	0.009
Cr	3.7	3.4	2.2
Hg	<0.001	<0.001	<0.001
Ni	<0.04	<0.04	<0.04
Pb	<0.04	<0.04	<0.04
Sb	0.10	0.18	0.47
Sn	<0.03	<0.03	<0.03
Zn	<0.1	<0.1	<0.1

4.2.2.5 Vestkraft Unit 1 co-firing wood (DK)

Description project

In the Vestkraft Unit 1 in Denmark full scale tests are executed with co-firing wood. This unit is a natural circulation boiler with a boiler capacity of 125 MW_e. The test in unit 1 were executed by replacing 2 of the 12 coal/oil burners by wood burners [Hansen, 1995].

Pre-treatment

The wood used in the tests originates from the furniture industry and it is not contaminated residual glue or related components. This wood has a calorific value of approximamly 19 MJ/kg_{dm} and an ash content of 0.45%. The wood is supplied in the form of pellets with a density of 500 kg/m³. These pellets are fed directly into cutters whereby they are grinded to sawdust. The sawdust is transported by air blowers to the burners through a 60 meter pipe with diameter of 450 mm [Hansen, 1995].

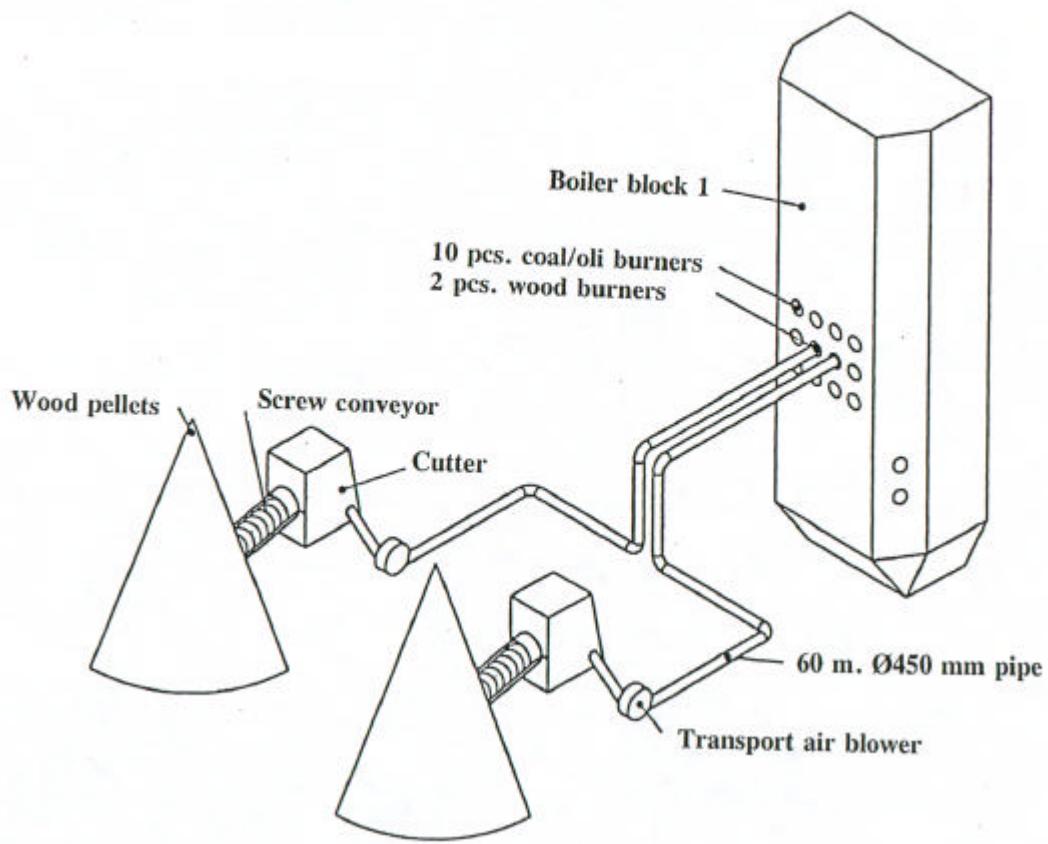


Figure Error! Unknown switch argument. **Wood processing plant [Hansen, 1995].**

Energy generation

The tests are executed with several amount of wood up to 20% of the energy input without any problems, even by the fairly large grain size of wood. It can be expected that larger shares of wood can be co-combusted if the wood is pulverised in example a hammer mill [Hansen, 1995].

Waste production.

By co-firing waste wood it is possible that the content of unburned carbon in the fly-ash will increase. The full scale tests did not show a discernible increment of the content of unburned carbon in the fly-ash. The amount of unburned carbon in the slag was increased from 4.5 to 7-11% when wood is co-fired.

The influence of co-firing of wood on ash and emissions are dominated by the binding of sulphur and chloride in the slag and fly ash. The tests did not show any further binding of these two components.

The tests show a decrease of NO_x emissions of 35% by a wood share of 15 to 20%. This decrease is not only caused by the lower nitrogen content of the fuel, because the nitrogen content of the fuel is reduced by 15%. The second reason for the decrease of the NO_x emissions are caused due to a low flame temperature during the tests [Hansen, 1995].

Remarks

The executed tests show a difference in behaviour of the electrostatic precipitator when wood is co-combusted. After a few days of operation a layer of dust is deposited in the ESP. This layer makes it difficult to remove the dust. To overcome this problem the electric voltage had to be reduced with the consequence that the removal of dust in the flue gas was at the same level as with firing coal alone.

Unloading from lorries and handling by loader tractors produce a lot of dust that cause problems for the employees [Hansen, 1995].

4.2.2.6 St. Andrä station retrofit with grate (A)

Description project

The 124 MW_e power station at St. Andrä has of origin a lignite boiler. In 1994 the firing system is changed to a hard coal system and modification has been made to make it suitable to the co-firing of biomass. **Error! Unknown switch argument.** gives an overview of the biomass grate project at St. Andrä. By the use of this process this station has used in 1997 45 kton of hard coal and 5 kton of biomass [Verbund, 1998].

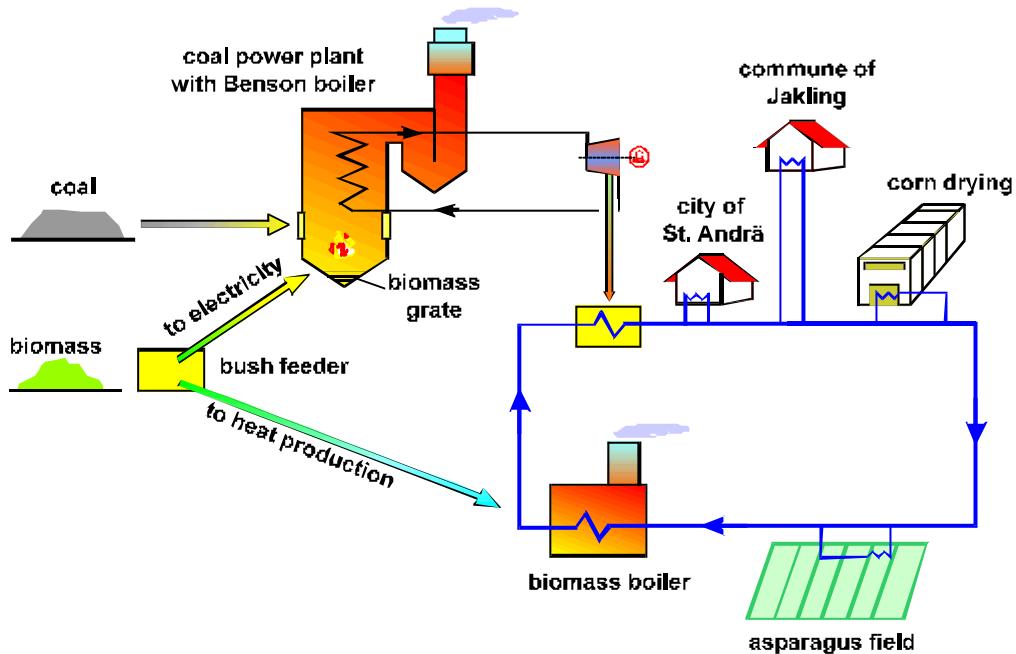


Figure Error! Unknown switch argument. Biomass grate project at St. Andrä in Austria

The essential modification to make the plant suitable to co-fire biomass exists of the installation of two moving biomass grates of 5 MW_{th} each at the bottom end of the combustion chamber (in the boiler hopper). The biomass feeders transport the fuel during combustion to the centre of the boiler, as shown in **Error! Unknown switch argument..** The produced ash from biomass and slag from coal will fall into the wet slag remover below the grate [Morey et al., 1998].

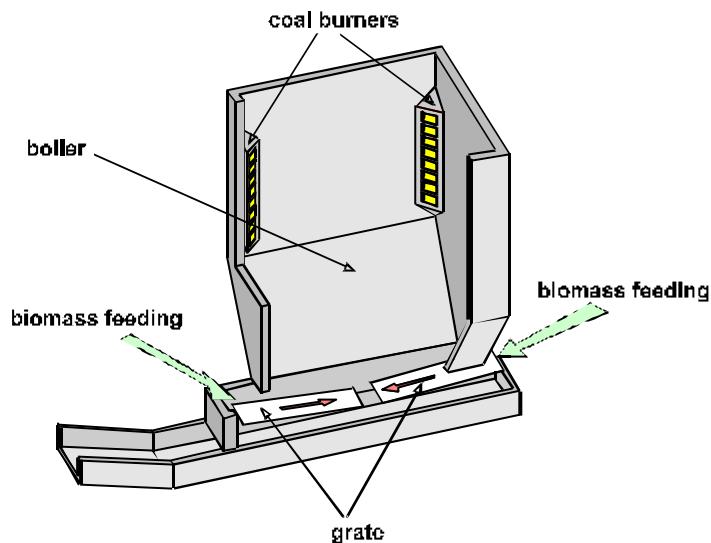


Figure Error! Unknown switch argument. Integrated biomass grate at the St. Andrä station [Mory et al., 1998]

Pre-treatment

The biomass used in this project consists mainly of bark with a moisture content of 50%. Besides this fuel a small amount of chopped wood and shredded forest residues is used. To overcome handling problems the biomass is cut with a shredder to a maximum length of 300 mm [Mory et al., 1998].

The biggest problem around this project is the storage and handling of the biomass. Storage became a problem because biochemical reactions occur during long storage (self-ignition, energy losses). Handling became a problem because of the impurities of the fuel. These impurities interrupt the conveying path [Mory et al., 1998].

Energy generation

According to the utility owner Verbund the efficiency of this system is approximately as high as of the coal unit. Heat losses and internal energy consumption are different, but not yet calculated [Mory, 1998].

Waste production.

The burn out of the project is very good. The unburned carbon in the mixture of coal slag and ash is far below 5%. The installation of a grate in the boiler does not have effect on the NO_x behaviour. During the tests the NO_x emissions remain always below 300 mg/Nm³ [Mory et al., 1998].

Remarks

It is difficult to estimate the costs of the project executed in the St. Andrä station, because the plant those already have a biomass storing and conveying system from the local heating centre. According to the Austrian utility Verbund the extra costs for the co-combustion system (grates and additional conveying components) were approximately 1.4 MECU [Mory et al., 1998].

4.2.2.7 Zeltweg station with external gasifier (A)

Description project

The Zeltweg power plant does have an installed capacity of 137 MW_e and was designed to combust lignite. In 1982 boiler adaptations were made to make it suitable to combust hard coal (tangential fired). In January 1998 the plant was expanded with an external CFB reactor to converse biomass by partial gasification. By the use of this reactor the system is very flexible to a wide range of biomass streams. The produced products of the gasifier consists of sensible, heat, low calorific value gas end fine combustible char particles. All these products are transported to the coal boiler. The produced gas is in this project used as reburning fuel to reduce the NO_x emissions. **Error! Unknown switch argument.** gives an overview of the Zeltweg biomass project [Mory et al., 1998].

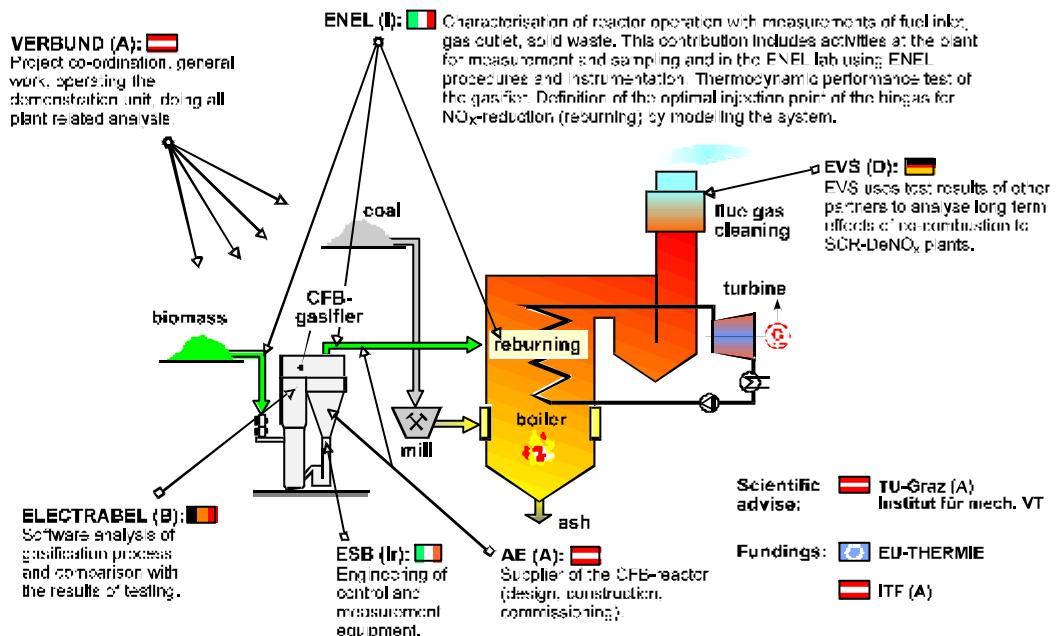


Figure Error! Unknown switch argument. The Zeltweg biomass project [Mory et al., 1998]

Pre-treatment

The biofuel used in this project consists mainly of bark with a moisture content of 55%. The particle size of the biomass stream is limited by the feeder of the system and is in this way limited to 30*30*100 mm. No further pre-treatment of the used biomass of this system is necessary, because of its flexibility [Mory et al., 1998].

The produced char in the gasifier is ground to fine powder, which guarantees a complete combustion in the boiler [Mory et al., 1998].

Energy generation

The power range of the gasifier was varied between 5 and 13 MW_{th}, depending on the humidity of the biomass [Mory et al., 1998]. According to the utility owner Verbund the efficiency of this system is approximately as high as of the coal unit. Heat losses and internal energy consumption are different, but not yet calculated [Mory, 1998].

Waste production.

The product gas is used as a reburning fuel in the existing coal boiler, to decrease the NO_x emissions by converting NO_x to nitrogen. During the tests 3% of the total thermal input results with this technology to a decrease of the ammonia water consumption of the SNCR system of 10-15% [Mory et al., 1998].

Remarks

It is difficult to estimate the costs of the project executed in the Zeltweg station. According to the Austrian utility Verbund the additional costs for the co-combustion system were approximately 2.8 MECU [Mory, 1998].

4.2.2.8 Amer power with external gasifier (NL)

Description project

Distribution Company PNEM in The Netherlands has planned to co-combust gasified low quality demolition wood (not suitable for the chip board industry) in Unit 9 of the Amer Station in Geertuideberg. Unit 9 of the Amer Station is a 600 MW_e powder coal station which delivers besides electricity also 350 MW_{th} district heating. To limit the emissions this unit has low NO_x-burners, an electric precipitator and a wet flue gas desulphurisation installation. With a coal input of 1.5 million ton per year the unit produces 600 MW_e with an electric efficiency of 41.5% and an overall efficiency of 60% [Dijck, 1995]. At this moment the plant is under construction and will be operational before the end of 1999 [Willeboer, 1998].

The project exists of a separate circulating fluidised bed (CFB) gasifier in which the waste wood is gasified. The produced gas is cooled in a gascooler and cleaned in a filter. After filtering the gas is injected in the existing boiler.

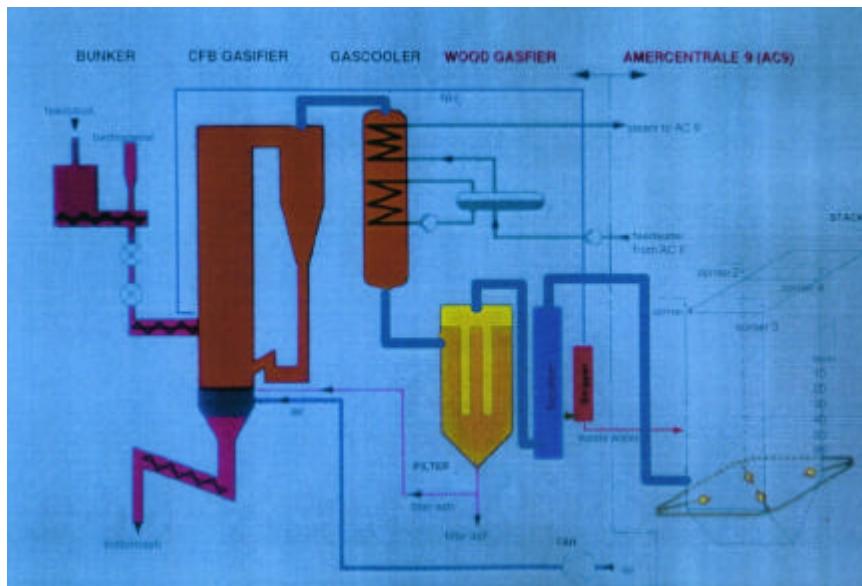


Figure Error! Unknown switch argument. Wood gasification flow-chart [Dijck, 1995].

Pre-treatment

The demolition wood will be gathered by a apart company and delivered as chips with a size of maximum 5 cm [Jong, 1998]. These chips will be cleaned of big parts by a rotating disk separator and a magnetic separator. The chips will be gasified operating at temperatures of 800-950°C with the addition of bed material and limestone or dolomite. The product gas passes a cyclone and cooled down in a gas cooler to a temperature of about 200 to 250°C. After cooling the gas is dedusted in a bag house filter and disconcerted of ammonia with water in a scrubbing section. After this scrubber, the gas is reheated to about 100°C and fed with special burners in the boiler [Willeboer, 1998].

Energy generation

By the annual use of 150 kton demolition wood there will be produced 90 MW_{th} or 30 MW_e [Jong, 1998]. The electrical efficiency of the system is 35-36% [Willeboer, 1998].

Waste production.

Since the plant is not build yet there are no emissions figures available. The emission requirements for the Amer 9 unit are for dust 20 mg/m₀³ and for NO_x and SO₂ 400 mg/m₀³. There are possible additional requirement based on BLA for the components HCl, HF, heavy metals and Hg [Dijck, 1995].

All the waste-streams (except the bottom and fly ash) are processed inside the installation [Willeboer, 1998].

4.2.3 Routes

The objective of this study is to determine if co-firing of biomass and coal waste from mining sites is possible in the coal fuelled Narcea I unit in Tineo in Spain. To achieve this goal it is necessary to indicate the routes in which the biomass can be co-fired in the Narcea I unit. **Error! Unknown switch argument.****Error! Unknown switch argument.** gives an overview of the possible routes to co-fire biomass and/or coal wastes from mining sites in the Narcea I unit.

The first route pretends to have no pre-treatment at all of the biomass stream. The biomass chips will not be dried before entering the coal mills, because the coal mills could be able to dry the chips by primary air. For the second route the biomass chips will be (partly) dried and pulverised before it enters the boiler. This route can be executed with a reburning technology (route 3) or mixed up with the existing coal stream (route 2). The fourth route corresponds with the first route with the exception of pelletising of the streams, which could lead to a homogenous and easily transportable fuel stream. With the fifth route the biomass will be pyrolysed in a separate unit and the flue gas will be burned in the boiler with or without reburning technology. The remainder char coal can be mixed up with the coal and pulverised by the existing coal mill. The gasification technology will be the base of route six. For this route the biomass chips will be gasified and the produced clean gas can be used in the boiler with or without reburning technology. The remainder routes (route 7, 8, 9) are retrofit options of the boiler. The simplest retrofit option is to install an integrated grate into the combustion boiler, as shown in route seven. In this route to the Narcea boiler will be included a grate. Route eight will be the retrofit option to a bubbling fluidised bed boiler. For route nine the existing boiler will be retrofitted to a circulating fluidised bed boiler.

In the following eight sections the mentioned routes will be discussed by a description of the routes, advantages and disadvantages of the routes, expected costs and the expected performance of the routes.

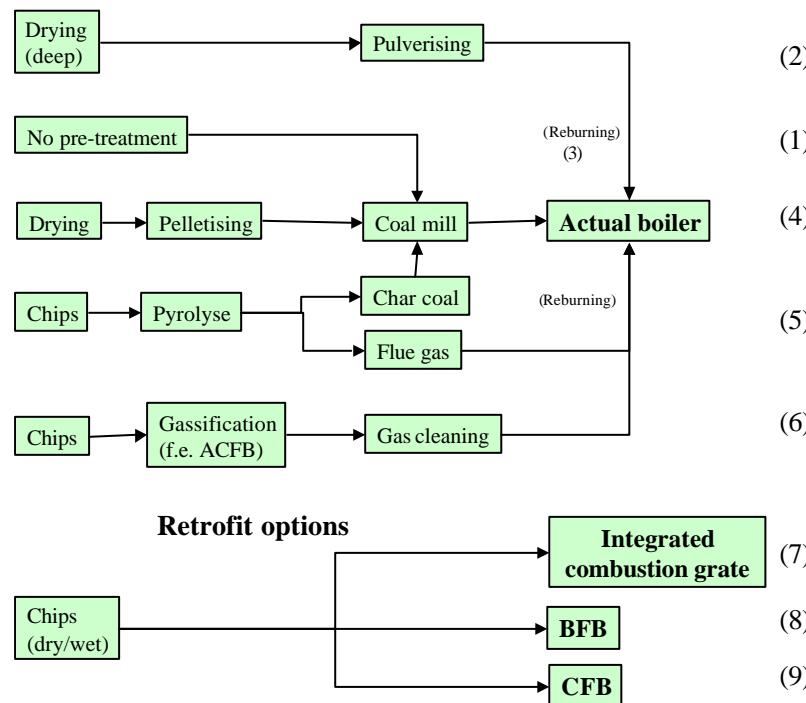


Figure Error! Unknown switch argument. Routes to co-fire biomass and/or coal waste from mining sites in the Narcea I unit.

4.2.3.1 Route: Direct combustion

.1.1 Description

The cheapest solution for the co-combustion of biomass chips in a pulverised coal plant is to have no pre-treatment of the biomass stream and to add the biomass directly to the coal flow. Unfortunately the existing coal mills are not suitable to grind coarse biomass and therefore grinding should take place before entering the coal mill or the mill must be replaced by a suitable mill which is more flexible for the input.

Unit I of the Narcea power station makes use ball mills of Foster Wheeler as shown in **Error! Unknown switch argument..** These ball mills consist of a large rotating cylinder containing different sized solid steel balls. The cylinder rotates as coal is fed into the cylinder. The coal falls to the bottom of the cylinder where it is crushed by the steel balls. This crushing principle is not completely suitable for the residues, since they have a fibre structure. Therefore, the size of particulates of the residues have to be reduced before they are entering the ball mill.

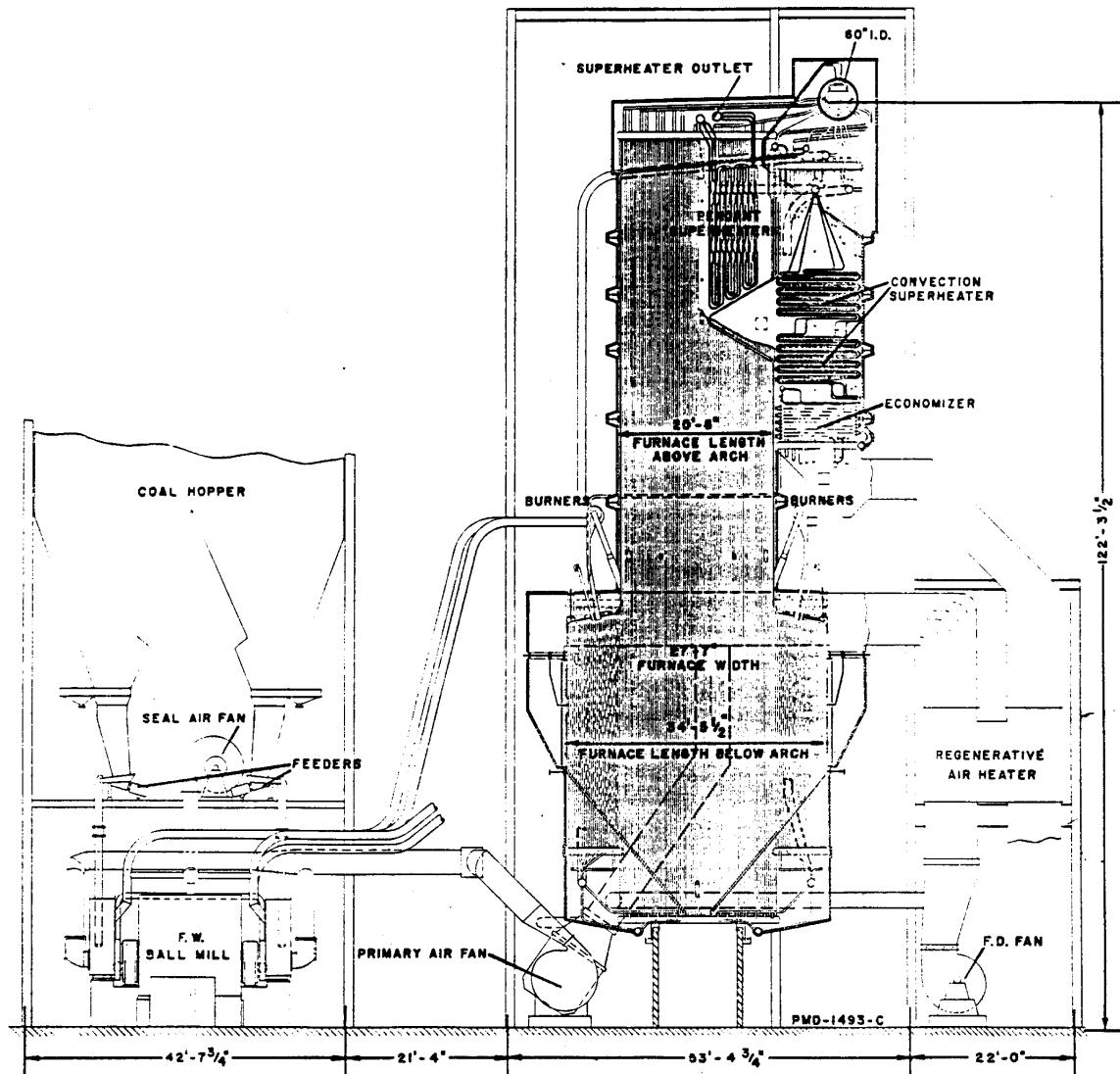


Figure Error! Unknown switch argument. Crosscut of Unit I of the power plant in Narcea [Union Fenosa Ingeniería, 1998]

According to Unión Fenosa Ingeniería the top size of the wood waste particles has to be <6 mm when biomass is cofired in an existing pulverised coal boiler with simultaneous or separate feedings [González et al., 1998]. To create particles with a the top size of the wood waste particles of <6 mm several techniques are suitable, but the sector in which size reduction is applied is typical. If the size system is used in the forestry sector the choice could be a harvest-integrated chipper (4-50 mm), a mobile chipper (4-50 mm) or a stationary chipper (4-50 mm) on the field to produce coarse chips.

The size reduction of the forest residues can take place decentral on the land or can take place centralised by the power plant. Central chipping has the advantage that one stationer chipper is needed, whereas decentral chipping needs at least one mobile chipper.

Decentral chipping can take place for example with a Finnish harvester called the Chipset 536 C. This Chipset consists of an tractor, 15 m³ container and crane. Forest residues (maximum 35 cm) are picked up by the crane and loaded into the container.

When the 15 m³ container is full this container can be emptied in a standard container of 45 m³ and transported to the plant. According to the Swedish company Logset the Chipset is 30% cheaper than traditional methods, were the forest residues are transported to a central point in the field and chipped. According to the producer the output of the Chipset is 40 m³_{los} per hour [Sten, 1997].



Figure Error! Unknown switch argument. Chipset 536 [Biowatti Oy, 1997]

The produced chips have to be transported to the conversion unit and if necessary pulverised. If the size system is used in the energy sector the choice could be a stationary crusher (50-200 mm), a chipper (4-50 mm) or a hammermill (<3 mm). In this case the biomass has to be delivered to the conversion unit as chips or as bales. The chips can be produced in the forestry sector as described before. The bales can be produced by a bale press consisting among other things of a drum with hydraulic driven gables. **Error! Unknown switch argument.** gives an impression of a forest residue press. An advantage of the production of bales compared to chips could be the storage problems of the chips. Chips are inclined towards decomposing, whereas bales can be stored for a long period.

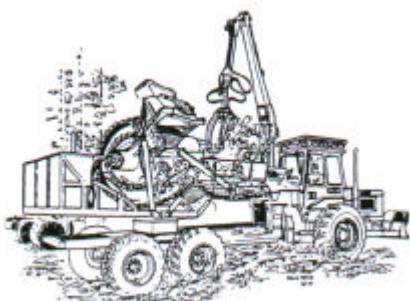


Figure Error! Unknown switch argument. Forest residue press [Bala Press, 1998]

The choice of the sizing system depends among other things on the energy consumption, the investment costs, the operating/management costs and the size required in the conversion unit. **Error! Unknown switch argument.** gives an indication about energy consumption, costs and length of biomass for different sizing options divided by forestry and energy sector.

Table Error! Unknown switch argument. Indicative information about energy consumption, costs and length of biomass different sizing options divided by forestry and energy sector [Heuvel, 1995].

	Energy consumption (MJ/t _{dm})	Costs (ECU/t _{dm})	Length of output (mm)
Forestry sector			
Bales	²	²	²
harvest-integrated chipper	450 ¹	95 ¹	4-50 ¹
mobile chipper	450 ¹	95 ¹	4-50 ¹
stationary chipper	450 ¹	95 ¹	4-50 ¹
Energy sector			
stationary crusher (chunks)	480 ¹	15-60 ¹	50-200 ¹
stationary chipper (chips)	860 ¹	15-95 ¹	4-50 ¹
stationary hammermill (fines)	390-1470	n.a.	<3 ¹

¹ [Heuvel, 1995]

² Figures presented in [Andersson et al., 1997], but these figures are orientated on a Swedish system.

To avoid an extra installation at the conversion unit a solution could be the replacement of the existing ball mills by suitable pulveriser, like the Arita pulveriser of the Deutsche Babcock Riley Incorporation. In this pulveriser the crusher-dryer, pulverising and fan sections are combined in a single shop - assembled unit. According to Unión Fenosa Ingeniería this mill has a higher tolerance for biofuels and tests with a combination of coals and biofuels show good performances up to 8% biofuel [González et al., 1998].

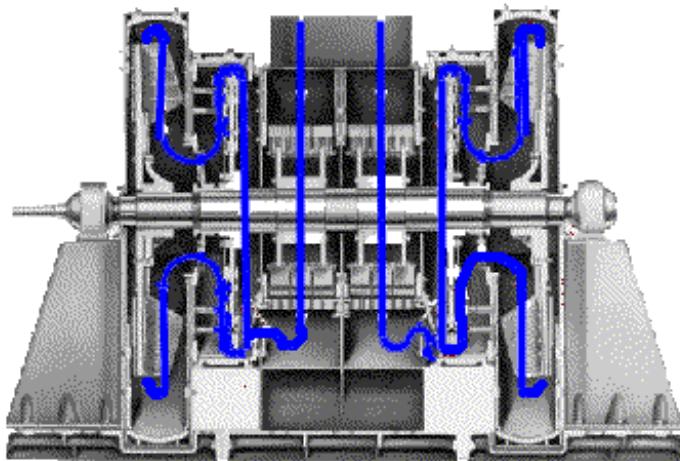


Figure Error! Unknown switch argument. DB Riley Arita Pulveriser [DB Riley, 1998]

.1.2 Advantages/Disadvantages

Making use of the existing ball mills could lead to deterioration in pulveriser performance. According to Unión Fenosa Ingeniería the levels of fuel >200 mesh and >50 mesh will increase with a biofuel percentage of more than 5% [González et al., 1998]. To overcome this problem the existing ball mills must be replaced by suitable mills.

Another limit for the direct combustion of biomass is the moisture content of the biofuel. If the wet biomass is inserted into the coal mill, it will partly be dried and preheated into the coal mill by heated air of the fans in the mills. If the moisture content is too high the supply of drying air must be increased and this can influence the gas cleaning system negatively. This problem occurred in the Maasvlakte power station in which sewage sludge, de-inking sludge and compost residues are cofired, as described in chapter **Error! Unknown switch argument..** These biomass streams are mixed up and pelletised to homogenous pellets with a moisture content of 50%. In the Maasvlakte station the biomass pellets and coal are milled, partly dried and preheated into the coal mill. This drying takes place by heated air of the fans in these coal mills. Because of the larger gas flow the gas cleaning is not functioning as it should be. Therefore, the biomass have to be pre-dried in the Maasvlakte project. In the Narcea case the co-combustion of the wet biomass could reduce the particulate removal efficiency in the electrostatic precipitators (ESP).

.1.3 Expected costs

Indicative cost figures of different sizing options are given in **Error! Unknown switch argument..**

Cost figures for the replacement of the existing mills to mills which are more flexible are not available.

.1.4 Expected performance

Error! Unknown switch argument. gives an indication of the energy consumption of pulverising woody materials into fines.

4.2.3.2 Route: Drying, pulverising and existing burners

1.5 Description

Since the coal mills are able to handle particles with specific size the biomass has to pre-treated before entering the coal mills. Because biomass with a high moisture content is tougher than dry biomass, the best way to pulverise the biomass is to dry the biomass before pulverising. In this way a lower energy consumption for pulverising is needed, but a higher energy consumption for drying is the disadvantage. **Error! Unknown switch argument.** gives an overview of possible drying technologies for biomass and **Error! Unknown switch argument.** gives the results of the inventory of the drying technologies as described in **Error! Unknown switch argument..**

Table Error! Unknown switch argument. Results of the different drying technologies.

Drying types	Direct/indirect	Status technology	Energy consumption	Capacity (twe/h)	Specific investment (kfl/twe/h)
Biological	direct (decomposed heat)	demonstration	2.5 GJ/twe	94	400
Low temperature	indirect (flue gas, 54°C)	pilot	-	-	-
Rotary drum	direct (flue gas, 300°C)	commercial	-	18	417
	indirect (steam, 15 bar)	commercial	-	8	375
	direct (flue gas, 180°C)	commercial	-	17	717
Fluidised bed	indirect (steam, 40 bar)	commercial	-	6	417
Steam	indirect (steam, 12 bar)	commercial	-	10	700
	indirect (steam, 24 bar)	commercial	-	40	450
Recompressive	-	demonstration	-	19	485

After drying the biomass can be pulverised to the required size. According to Unión Fenosa Ingeniería the size of the particles of the biomass cofired projects in the USA do not exceed 6 mm [González et al., 1998]. On the contrary the Austrian utility Verbund reports that the particle size must not exceed 0.4 mm to prevent unburned carbon in fly ash [Mory et al., 1998].

To reduce the size of the biomass particles several sizing technologies are possible as described in section **Error! Unknown switch argument..**

.1.6 Advantages/Disadvantages

The major disadvantage of this route is the energy consumption for drying the biomass, whereas the advantage is the lower energy consumption to pulverise the biomass.

.1.7 Expected costs

Indicative cost figures of different sizing options are given in **Error! Unknown switch argument..**

.1.8 Expected performance

Indicative energy consumption of the different drying technologies is given in **Error! Unknown switch argument..**

4.2.3.3 Route: Drying, pulverising and separate burners

.1.9 Description

With this route the size of the biomass will be reduced to chips and these chips will be dried. The dried chips will be grinded to small fines before entering the boiler with or without reburning technology. If separate burners are used the particles size of the biomass is independent of the capability of the coal mill and therefore larger particles can be used. In this way it maybe possible to produce the chips in the forestry sector as described in section **Error! Unknown switch argument..**

Error! Unknown switch argument. gives an overview of possible drying techniques for the forest residues that can be used in this project.

To reduce the size of the biomass particles several sizing technologies are possible as described in section **Error! Unknown switch argument..**

The dried (and pulverised) biomass can be burned by the mean of reburning technology. Reburning is a technique in which fuel is added to the secondary combustion zone in a boiler. By adding this fuel in second combustion zone the NO_x emissions can be reduced by 50-60% [Zamansky et al., 1998]. Higher reduction potentials are possible if fuels are used which includes nitrogen and alkali compounds. Since biomass already includes these components, it becomes a candidate as reburning fuel [Zamansky et al., 1998].

In 1997 the American Energy and Environmental Research Corporation has executed experiments in which biomass is injected into the secondary combustion zone. According to these experiments biomass basic reburning achieved 50% NO_x reduction at 10% biomass heat input. With a heat input of 23% biomass a NO_x reduction was achieved of 74%. Experiments with coarse biomass and fine biomass showed that the size of the particles is more important for lower biomass concentrations [Zamansky et al., 1998].

Higher NO_x reduction figures are possible if overfired air is injected at 1200 K in the third stage, and aqueous urea is injected into the secondary combustion zone. According to these experiments reburning with 10% biomass achieved up to 86% NO_x reduction, whereas basic reburning resulted in 54% NO_x reduction.

.1.10 Advantages/Disadvantages

The major disadvantage of this route is the energy consumption for drying the biomass, whereas the advantage is the lower energy consumption to pulverise the biomass.

Another advantage of this route is by the use reburning technology a reduction of the NO_x emissions. According several sources these emissions can be reduced by 50-60% [Zamansky et al., 1998].

.1.11 Expected costs

Indicative cost figures of different sizing options are given in **Error! Unknown switch argument.**.. Cost figures of boiler adaptations are not available.

.1.12 Expected performance

Indicative energy consumption of the different drying technologies is given in **Error! Unknown switch argument..**

4.2.3.4 Route: Drying and pelletising

.1.13 Description

Advantages of pelletising the biomass streams are the increase in the homogeneity of the feed, the increase of the bulk density and the improvement of the combustion process by supplying a feedstock with better characteristics. The disadvantages of this manner of densification are the high investment costs and high energy input [Pierik et al., 1995].

In Maasvlakte coal-fired power station in The Netherlands a project is started to co-firing sewage sludge, de-inking sludge and compost residues. In the pre-treatment plant the biomass streams with average moisture content of 50% are mixed and pelletised to pellets. An open conveyer belt to the coal plant transports these pellets and halfway through conveyer belt the coals are added. In the coal plant the pellets and coal are mill and partly dried and preheated into the coal mills. This drying takes place by heated air of the fans in these coal mills [Janné, 1998].

For the Narcea plant pelletising the biomass and coal waste could be a problem, because no binder is available. To overcome this problem pelletising by high pressure and high temperature could be a solution. A disadvantage of this solution is the high-energy input to produce the pellets.

.1.14 Advantages/Disadvantages

Advantages of pelletising the biomass streams are the increase in the homogeneity of the feed, the increase of the bulk density and the improvement of the combustion process by supplying a feedstock with better characteristics. The disadvantages of this manner of densification are the high investment costs and high energy input [Pierik et al., 1995].

.1.15 Expected costs

No reliable sources available.

.1.16 Expected performance

No figures available.

4.2.3.5 Route: Separate pyrolysing

.1.17 Description

With this route the biomass is pyrolysed, producing a solid char fraction and pyrolysis gas. The pyrolysis gas can be burned in the boiler with or without reburning technology. The remainder char coal can be mixed up with the coal and pulverised in the coal mill.

In a feasibility study of ECN, willow is pyrolysed and produced product gas is clean by a tar cracker and a wet scrubber. The cleaned gas is compressed and co-combusted in a 335 MW_e IGCC plant. The size of the willow used in this study is reduced to 20*20*50 mm in a shredder with an energy consumption of 50 kWh per ton_{a.r.}. The produced biomass is dried in a rotary drum drier from a moisture content of 50% to 15%, using the flue gas as a drying medium. The pyrolyse takes place at a temperature of 450°C for 30 minutes.

.1.18 Advantages/Disadvantages

The first advantage of this route is the simply combining of the remainder char coal with the existing coal supply. The second advantage is the possibility of utilisation of the reburning technology. The third advantage is the location of the new installation. Whilst the installations in all retrofit concepts have to be placed close to the combustion chamber, what is seldom possible, the new installation can also be located in a larger distance to the combustion chamber.

Pyrolyse at a temperature of 600°C for 5 to 30 minutes will have a production of 33% liquid, 33% char coal and 33% pyrolyse gas [Kaltschmitt et al., 1997]. The production of the liquids could be a disadvantage of this technology, because they are unstable and will therefore give storage problems.

.1.19 Expected costs

In the feasibility study of ECN the investment costs for the pre-treatment section, which consists of pyrolyse, tar cracking , gas clean-up and compression, are 45 MECU (indicative) [Jansen, 1998].

See BTG reports, KEMA reports

.1.20 Expected performance

According to the pyrolyse model made by ASPEN^{plus} the overall efficiency of this pre-treatment pyrolysis process is 71.4%_{HHV} [Jansen, 1998].

4.2.3.6 Route: Separate gasification

.1.21 Description

With this route the biomass will be chipped and gasified. The produced product gas can be used in the boiler as an additional fuel with or without reburning technology. **Error!**

Unknown switch argument. gives an example of such a project executed at the Zeltweg Station in Austria as described in chapter **Error! Unknown switch argument..**

Error! Unknown switch argument. gives an overview of a CFB gasifier train. The biomass is fed into the lower part of the reactor which has an operating temperature of 800 to 1000 °C, depending on the fuel. The biomass starts to dry rapidly and pyrolysis of the biomass particles starts towards, char, tars and gases. All the products will flow upwards and will leave the reactor. In the following uniflow cyclone the solids (bed material and chars) and gases are separated. The solids will be fed in the lower part of

the gasification reactor and the chars will be combusted in this zone. The heat generated in this phase is required for the pyrolyse process and will be transported/stabilised by the bed material. The produced gas is cooled down in the air preheater before it is fed into the main boiler by the use of separate gas burners [Palonen et al., 1998].

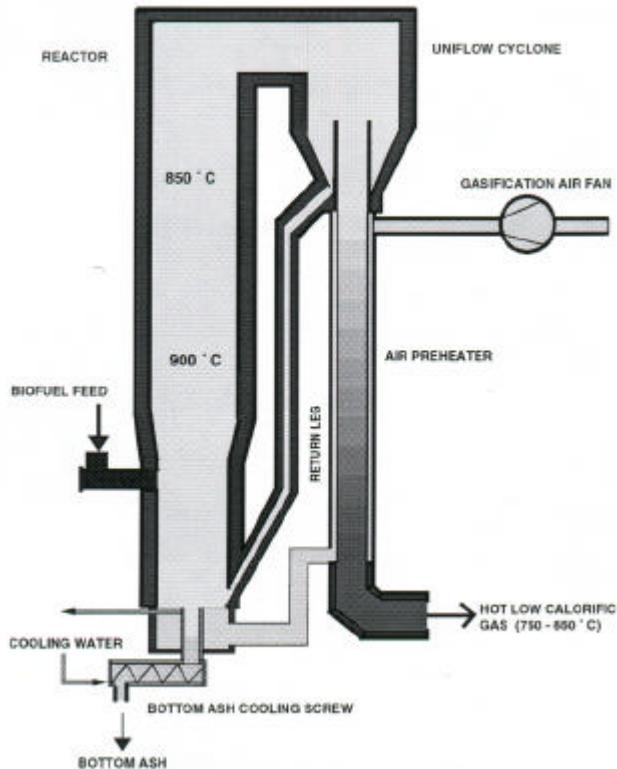


Figure Error! Unknown switch argument. CFB gasifier train [TEKES, 1996]

1.22 Advantages/Disadvantages

The main advantage of this way of conversion is the higher flexibility in arranging and integrating the main components into existing plants. This flexibility refers to the high moisture content of the biomass used and the size of the biomass. For example in the Kymijärvi station in Finland the biomass used can have a moisture content of up to 60%. The disadvantage of these wet fuels is the very low heating value of the produced gas. By the use of biomass with a moisture content of 50% the heat value of the gas was 2.2 MJ/m³. The size of the biomass is also an advantage of this route because it hasn't to be reduced till 10*3*3 cm, as shown in chapter **Error! Unknown switch argument..** This means that by the use of forest residues the biomass can simply be chipped (for example in the field) without a high energy input and no drying is needed.

Whilst the installations in all retrofit concepts have to be placed close to the combustion chamber, what is seldom possible, a gasifier with a lean hot gas duct can also be located in a larger distance to the combustion chamber. In the Verbund demonstration project at Zeltweg (chapter **Error! Unknown switch argument.**), the gasifier is outside the boiler house, more than 22 m away from the boiler.

An other advantage of this route could be use of the product gas as a reburning fuel in the existing coal boiler, to decrease the NO_x emissions by converting NO_x to nitrogen, as shown in chapter **Error! Unknown switch argument..**

Small modifications are required to the boiler.

.1.23 Expected costs

According to the Austrian utility Verbund the additional costs for the co-combustion system in the Zeltweg project were approximately 2.8 MECU for a gasifier with a power range of 5 to 13 MW_{th} [Mory, 1998].

.1.24 Expected performance

The power range of the gasifier was varied between 5 and 13 MW_{th}, depending on the humidity of the biomass [Mory et al., 1998]. According to the utility owner Verbund the efficiency of this system is approximately as high as of the coal unit. Heat losses and internal energy consumption are different, but not yet calculated [Mory, 1998].

4.2.3.7 Route: Retrofit to integrated co-combustion grate

.1.25 Description

As executed in the St. Andrä power plant (see chapter **Error! Unknown switch argument.**), it is possible to install a grate at the bottom end of the boiler hopper. In this way the flue gases from the biomass combustion rise directly into the furnace. According to Mory the installation of such grate will not lead to heat losses and it is not necessary to install complicated duct systems [Mory et al., 1998]. A disadvantage of the installation of a grate in the bottom of the boiler is the need of space below the boiler.

.1.26 Advantages/Disadvantages

The advantages of this routes are the flexibility of the fuel and the simple adaptations to the boiler. This flexibility refers to the high moisture content of the biomass used and the size of the biomass. For example in the St. Andrä power plant the biomass used has a moisture content of 50% and a size of maximum length of 30 cm. This means that by the use of forest residues the biomass can simple be chipped (for example in the field) without a high energy input and no drying is needed.

The disadvantages of this route are the required space below the boiler to install the boiler.

In coal-fired stoker the grate is protected for high temperatures by a layer of molten ash of the coal. Since a combination of biomass and coal will decrease the ash content of the fuel. According to NREL the grate may not be as well insulated and can be damaged [Piscitello, 1992].

.1.27 Expected costs

According to the costs figures of the installation of a grate in the St. Andrä station, the extra costs for the co-combustion system (grates and additional conveying components) are approximately 1.4 MECU for a 124 MW_e coal plant with two 5 MW_{th} moving grates [Mory et al., 1998].

.1.28 Expected performance

According to the utility owner Verbund the efficiency of this system is approximately as high as of the coal unit. Heat losses and internal energy consumption are different, but not yet calculated [Mory, 1998].

4.2.3.8 Route: Retrofit to bubbling fluidised bed boiler

.1.29 Description

In this route the Narcea boiler will be retrofit to a bubbling fluidised bed boiler. For a conversion of the existing boiler into a bubbling fluidised bed boiler, basically only the lower part of the boiler has to be modified. In the bottom of the furnace fluidising air nozzles have to be installed. **Error! Unknown switch argument.** shows the modification that takes place in the lower part of the boiler.

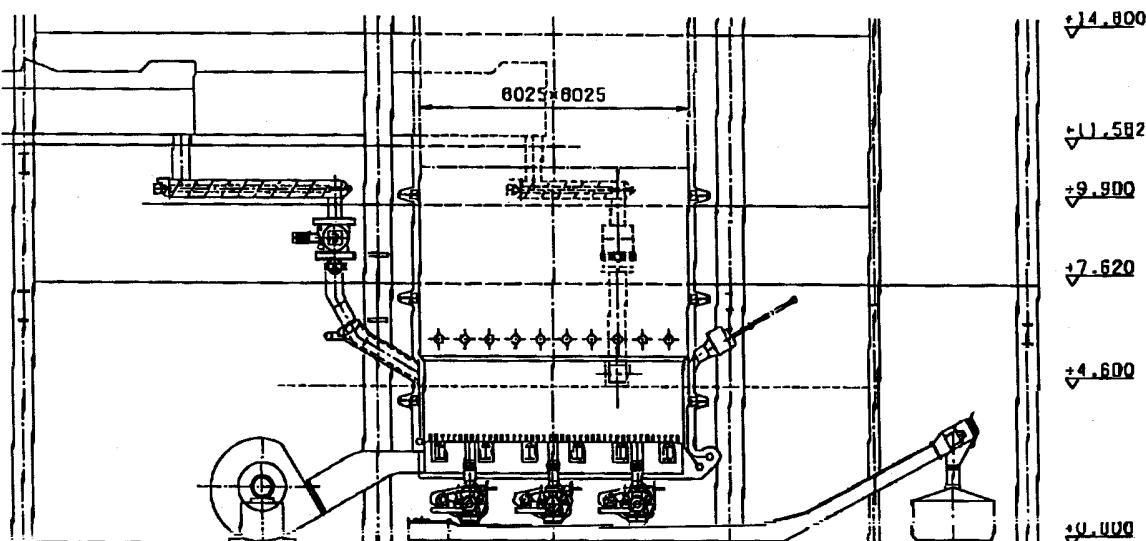


Figure Error! Unknown switch argument. Modified part of the pulverised peat boiler [Kinni, 1994].

The lower furnace walls have to be replaced. Replaced furnace walls and grate are constructed of gas tight membrane panels. The furnace walls utilise welded membrane construction, which matches the existing tube configuration above the cutline (**Error! Unknown switch argument.**). The furnace is provided with the required number and size of openings to accommodate the secondary and tertiary air ports, start-up burners, observations and access doors and instrumentation openings [Broek et al., 1995a].

The fluidising air nozzles must be welded between the tubes on the membrane floor. These tubes form a water cooled grate. The inactive portion of the fluidising medium (sand) created below the air nozzles openings serves as protection against erosion. The grate must be equipped with outlet chutes for coarse material, which can be opened manually. By temperature reading in various parts of the grate the coarseness of material can be measured. When temperature readings differ considerably from each other, this means that bed material has to be evacuated in that section of the grate. From there the coarse material is removed to a coarse material silo [Broek et al., 1995a].

Sand can be used as a fluidising medium. Because of low fluidising velocities sand losses will be minimal.

A flue gas recirculation system must be constructed to control the bed temperature by mixing the flue gas with fluidising air and thus lowering the oxygen content in the bed. The flue gas must be extracted at the pressure side of the induced draught fan, which pumps the flue gas into the chimney [Broek et al., 1995a].

.1.30 Advantages/Disadvantages

Modification of the existing boiler to a bubbling fluidised bed (BFB) has the advantage that the BFB boiler provides flexibility with respect to co-firing of the streams in any combination. In this no drying and pulverising of the biomass is necessary. The modifications to the existing boiler are relatively modest and experience with this kind of retrofitting are available in for example Finland.

.1.31 Expected performance

In 1995 a study has been executed by the Department of Science, technology and Society of Utrecht University to estimate the expected overall average efficiency of a 45 MW_e peat plant to a bubbling fluidised bed plant. For this peat plant the expected overall average efficiency is estimated at 30%_{LHV} [Broek et al, 199a].

.1.32 Expected costs

In 1995 a study has been executed by the Department of Science, technology and Society of Utrecht University to estimate the initial retrofit costs of a 45 MW_e peat plant to a bubbling fluidised bed plant [Broek et al., 1995a]. The expected costs to retrofit this plant were estimated as 8.5 - 12.9 MECU₁₉₉₅ or 189- 299 ECU/kW_e. According to this study about 4 MECU₁₉₉₅ was needed for basic fluidised bed retrofit. **Error! Unknown switch argument.** gives an overview of the initial retrofit costs of the retrofit to a BFB boiler.

4.2.3.9 Route: Retrofit to CFB boiler

.1.33 Description

With circulating fluidised bed (CFB) boilers the particulates escape from the boiler with the flue gases. The primary gas velocity is increased in comparison with a BFB boiler, as a result of which more of the particulates are entrained in the gas stream. The particulates and inert bed material that leave the boiler are separated from the flue gas by a coupled cyclone, as shown in **Error! Unknown switch argument..**

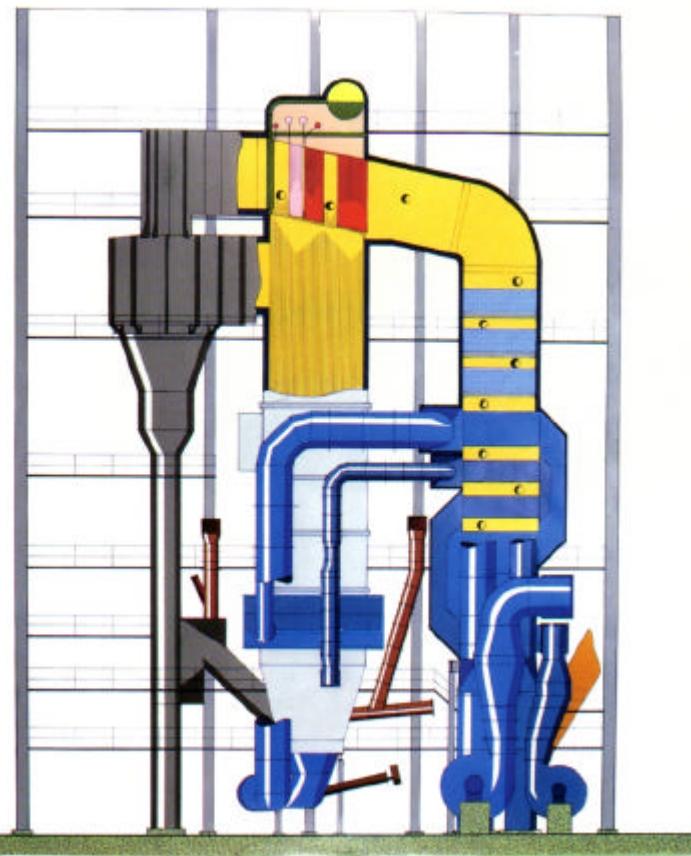


Figure Error! Unknown switch argument. The 80 MW_{th} CHP Grenaa CFB boiler in Denmark fuelled with straw and coal [TEKES, 1996]

No information is available on retrofitting and pulverised coal boiler to a CFB boiler.

.1.34 Advantage/disadvantage

The advantage of the CFB boiler is the higher carbon burnout efficiency, because of longer residence time.

A disadvantage of retrofitting the existing boiler to a CFB boiler is the need of space around the boiler, because the CFB boiler needs a cyclone. This disadvantage can be eliminated by the retrofit to a CYMIC (cylindrical multi inlet cyclone) CFB boiler. This boiler type has an internal cyclone, which gives the benefit of a simple and compact design. Besides the mentioned advantages the CYMIC boiler is developed to avoid the weaknesses of earlier CFB construction. These weaknesses were complicated uncooled construction of the cyclone with heavy refractories, difficult hot expansion joints, and as a result rather low availability. The straight cyclone minimises the possibility to erosion and there are no difficult areas to fix the refractories. The first demonstration/commercial CYMIC CFB boiler was built in Lieksa in Finland. This boiler has peat and bark as fuel [Kokko et al., 1997] , [Kokko, 1998].

Another disadvantages of CFB boiler in comparison to the BFB boiler are the less fuel size design flexibility and the less fuel size switching flexibility [Broek et al., 1995].

.1.35 Expected costs

The CFB boiler needs a cyclone and therefore the system is enlarged. This can express itself in the higher capital costs in comparison within the BFB boiler.

The investment costs for the whole CYMIC boiler in the 8 MW_e Lieska plant are 60 MFIM in the year 1993. The costs of the boiler with auxiliaries are one third of the whole plant cost. The investment costs for the whole CYMIC boiler in the 30 MW_e Rauma plant are 100-125 MFIM (low investment costs by exiting boiler building, water treatment, tanks, oil system etc.) [Kokko, 1998]. The costs figures of retrofitting the existing boiler are not available

.1.36 Expected performance

Greater fan power requirement needed to maintain the high velocity through the bed. therefore, the energy consumption of the boiler will higher compared to the BFB boiler.

The CYMIC CFB boiler in Lieska in Finland has a boiler efficiency of 91% and has a capacity of 8 MW_e and 22-26 MW_{th}. This plant is in operation from 1993. The CYMIC CFB boiler in Rauma in Finland has a boiler efficiency of 92% and has a capacity of 30 MW_e and 130 MW_{th}. This plant is in operation from 1997.

4.2.3.10 Route: Separate combustion unit

.1.37 Description

By this route the biomass is combusted in a separate unit and the produced fluegas is injected into the boiler. This separate unit can be for example combustion chamber with a grate firing system, but with uncooled walls [Mory et al., 1998].

.1.38 Advantage/disadvantage

The advantage of this system are the very simple adaptation of the existing system and the flexibility to the biomass is very high

This system has three major disadvantages. Firstly, there must be enough space around the existing boiler to build the new combustion chamber. Secondly, the temperature in the combustion chamber must not exceed 1.000 °C, to prevent slagging on the grate. Thirdly, the flue gas volume must be enlarged to keep the temperature below 1.000 °C [Mory et al., 1998].

Further on standard grate systems are not gas tight and cannot operate with over pressure to press the hot gas to the coal boiler. But fans, working at such high gas temperatures, are not available. So only the underpressure in the coal boiler success the gas, what leads again to larger cross-sections in the hot gas pass [Mory et al., 1998].

.1.39 Expected costs

No figures available.

.1.40 Expected performance

No figures available.

4.2.4 Conclusions

In this report a review is given of the state-of-the-art in co-firing coal, biomass and coal waste and this report also determined the routes in which the biomass can be co-fired in the Narcea I unit.

In the review of the state-of-the-art in co-firing several relevant cofiring projects are discussed, by identifying advances and operational problems so far in relation to three parts of the application: pre-treatment, energy generation and waste production. For pre-treatment an assessment is made for the drying, sizing, screening and storing of biomass. For energy generation the behaviour and consequences of combustion are studied, including efficiency and ranges of share of fuels mixtures (in relation to composition and combustion behaviour). Also the waste production is discussed by the characterisation of ashes and emissions including heavy metals and levels of NO_x, SO₂, and particles. The conclusion of this review is that cofiring of biomass is not a complex technology, but by the implementation of this technology several problems occurred by the reviewed projects. If co-combustion of biomass in the Narcea I unit will be executed then attention must be paid to the problems in the reviewed projects.

Another conclusion of this review is that the suggested modifications to the Narcea I unit in the project programme are possibly not the most cost effective, environmentally or energetic the best solution for this plant. In the project programme the technological options considered are injection through the burners of the plant modified to fit to this new fuel or injection in other parts of the boiler looking for an reduction of NO_x effect. This review shows that the technology bounding beforehand could lead to sub optimal conditions.

After the assessment of the previous studies an overview is given of the possible routes to co-combust biomass in the Narcea I unit. The objective of this assessment is to determine if co-firing of biomass and coal waste from mining sites is possible in the coal fuelled Narcea I unit in Tineo in Spain. To achieve this goal the routes are indicated and discussed by a description of the routes, advantages and disadvantages of the routes, expected costs and the expected performance of the routes. To make a good judgement of these nine routes a evaluation table is produced with several criteria. In this way a value judgement can be given of the routes. **Error! Unknown switch argument.** shows the described routes and the value judgement.

For one criteria it is possible to give an impression of quality score between the several routes. It is not possible to give an overall conclusion of all the criteria by an addition of all the quality scores, since each criteria has an other weight to the total. A way to sum up all the scores is by use of weight factors for each criteria. These weighing factors can be created for example by an expert group. However, this study limits to the quality score of one criteria and a subjective conclusion.

A conclusion of this evaluation is that the cheapest routes (routes 1-3) are the routes suggested in the project programme of this project. Another advantage of these suggested routes is that these routes do not need much space around the existing boiler. In this way the implementation of these routes will not lead to problems to the densely developed area of Unit I. The third advantage of the three cheapest routes is the simplicity of the modifications to the plant. However, it is not possible to make a judgement by these three criteria alone. Every criteria must be deliberated to come to a definitive judgement for the best co-combustion option for the Narcea I unit. In our

opinion the in the project programme suggested technology bounding beforehand could lead to sub optimal conditions.

Table Error! Unknown switch argument. Evaluation of routes

Route	No pre-treatment	Drying pulverising	Separate	Pettetising (4)	Pyrolyse (5)	CFB gasifier	Grate (7)	BFB boiler (8)	CFB boiler (9)
Construction related									
simplicity of retrofitting	++	+	+	0	-	-	0	-	--
needed space around the	++	++	++	+	+	+	--	-	--
Fuel related criteria									
fuel moisture design	--	++	++	+	+	++	++	+	++
fuel size design flexibility	--	-	++	-	++	++	++	+	+
fuel moisture switching	--	+	++	+	+	++	++	0	+
fuel size switching flexibility	--	+	+	0	+	+	++	0	0
Efficiency related criteria									
boiler efficiency					0	++	0	0	+
carbon burnout efficiency	--	-	-	--	=	++	0	+	++
modest excess air								+	+
modest fan capacity								-	--
Emission related criteria									
NO _x reduction	0	0	++	0	++	++	0	0	0
solid waste production	-	--	--	-	--	--	--	-	-
Retrofit costs per kW _e	--	-	0	-	++	++	+	++	++

All criteria are formulated in the positive way, which means that a plus sign always indicates a positive characteristic. The signs “++”, “+”, “0”, “-“ and “- -“ represent a decreasing line of quality score on a certain criterion. The empty cells indicate that it is not possible to draw a conclusion from the gathered information.

4.2.5 References

- Andersson, G., B. Norden, *Baling of logging residues - a systems analysis*, Skogforsk, Uppsala, Sweden, 1997.
- Bala Press, *Forest residue press*, BALA Press AB, Nossebro, Sweden, 1998.
- Beekes, M.L., *Co-combustion of biomass and waste streams*, KEMA Environmental Technology, Arnhem, The Netherlands, 1995.
- Biowatti Oy, *Clean energy from wood*, Biowatti Oy, Espoo, Finland, 1997.
- Broek, R. v. d., A. Faaij, A. van Wijk, *Biomass combustion power generation technologies*, Department of Science, Technology and Society, Utrecht University, 1995.
- Broek, R. v. d., G. Blaney, A. Faaij, *Retrofit options to enable biomass firing at Irish peat plants*, Department of Science, Technology and Society, Utrecht University, 1995.
- Broek, R., A. Faaij, A. van Wijk, *Biomass combustion power generation technologies*, Department of Science, Technology and Society, Utrecht University, Utrecht, The Netherlands, 1995b.
- Broek, R., A. Faaij, *Retrofit options to enable biomass firing at Irish peat plants*, Department of Science, Technology and Society, Utrecht University, Utrecht, The Netherlands, 1995a.
- Davis, K., *Personal communication*, Deutsche Babcock Riley Incorporation, Worcester, Massachusetts, USA, 1998.
- DB Riley, *Atrita® Pulverizer*, Deutsche Babcock Riley Incorporation, Worcester, Massachusetts, USA, 1998.
- Dijck, F.W.H.M. van, *Co-combustion of gasified waste wood in a coal fired power plant*, Proceeding of the International NOVEM/IEA Symposium Co-Combustion of Bio-Fuels, Nijmegen, The Netherlands, November 1995.
- EPON, *Energy from waste and biomass*, nv EPON Power Generation, Zwolle, The Netherlands, 1995.
- EZH, *Coal-fired power station Maasvlakte Rotterdam*, N.V. Electriciteitsbedrijf Zuid-Holland, 1997.
- Gast, C.H., H.P.A.M. van der Staak, J.G. Visser, *Bijstookproeven met rioolwaterzuiveringsslip in Hemweg* & KEMA Milieu Technologie, Arnhem, 1995 (in Dutch).
- Gast, C.H., J.G. Visser, *Stookproeven met poederhout/poerderkool in de 1 MWth proefketelinstallatie*, KEMA, Arhem, 1993.
- González, J.A., J.A. Martínez, *Potential of Group I Narcea Power plant for co-firing biomass*, Unión Fenosa Ingeniería, Madrid, Spain, 1998.
- Hansen, K.E., *Full scale test co-firing of wood in pulvitzed coal fired boiler and design study of 50% co-firing of wood at 89 MW_e coal fired boiler*, Proceeding of the International NOVEM/IEA Symposium Co-Combustion of Bio-Fuels, Nijmegen, The Netherlands, November 1995.
- Herhof, *The Herhof Stabilate Method*, Herhof-Umwelttechnik, Solms-Niederbiel, Germany, 1996.

- Heuvel, E.J.M.T., *Pretreatment technologies for energy crops*, BTG Biomass Technology Group BV, Enschede, The Netherlands, 1996.
- Janné, E.M., *Personal communication*, Maasvlakte coal-fired power station, The Netherlands, 1998.
- Jansen, D., *Co-gasification of coal and biomass: "Technical, economic, environmental and experimentally supported assessment of three concepts"*, in: Second conference "Coal and biomass: High-tech fuels for the future", Joule-Thermie 1996-1998, Brussels, 1998.
- Jensen, A.S., *Pressurized Steam Drying of Biofuel*, Niro A/S, Denmark, 1996
- Johnston, S.A., J. G. Cleland, R.S. Truesdale, T.C. Clark, W.D. Stancil, L.D. Ostlie, B. Weigel, *Engineering and Economic Evaluation of Whole Tree Burn Technology*, Electric Power Research Institute, Palo Alto, 1992.
- Jong, J.B.R.M. de, *Personal communication*, EPZ, Eindhoven, 1998.
- Kaltschmitt, M., A.V. Bridgewater, *Biomass gasification & pyrolysis. State of the art and future prospects*, CPL Press, Berkshire, United Kingdom, 1997.
- Kinni, J., , Tampella Power, Finland, 1994.
- Kokko, A., *Personal communication*, Kværner Pulping Oy, Finland, 1998.
- Kokko, A., J. Kinnunen, *CYMIC boiler in industrial scale*, Kværner Pulping Oy, UMP-Kymmene Rauma paper, presented at PowerGen Asia 97, Singapore, 1997.
- Konings, T., *Co-combustion of solid biomass with a Torbed reactor*, ISES Biomassdag, Apeldoorn, The Netherlands, 1996 (in Dutch).
- Lamarre, L., 'Electricity from Whole Trees', *EPRI Journal* January/February, 1994
- Mercer, A., *Industrial Drying Technologies*, CADDET, Sittard, the Netherlands, 1994
- Meuleman, B., A. Faaij, *Behaviour of heavy metals in a coal plant and a municipal solid waste incinerator*, Department of Science Technology and Society, Utrecht University, Utrecht, 1997 (in Dutch).
- Morrison, G. F., J.M. Ekmann, S.M. Smouse, J.C. Winslow, M. Ramezan, N.S. Harding, *Cofiring of coal and waste*, London, IEA Coal Research, 1996.
- Mory, A., J. Tauschitz, *Electricity production from biomass in pf boilers in Austria; the biomass gasification project BIOCOCOMB (EU-Thermie) and the biomass co-combustion grate project*, Verbund-Elektrizitätserzeugungs-GmbH, Geschäftsstelle Klagenfurt, Klagenfurt, Austria, 1998.
- Mory, A., *Personal communication*, Verbund-Elektrizitätserzeugungs-GmbH, Geschäftsstelle Klagenfurt, Klagenfurt, Austria, 1998.
- MTM, *Herhof "Trockenstabilat Verfahren"*, Technical Office MTM, Munstergeleen, The Netherlands, 1997.
- Münster, K., *Personal Communication*, Stork Engineering, Goteborg, Sweden, 1997.
- Nemesis, *Making the Most of LOW-VOLATILE*, Nemesis Intelligence Worldwide, Klagenfurt, Austria, 1998.
- Ostlie, L.D., *The Whole Tree Burner: a New Technology in Power Generation*, Energy Performance Systems, Minnesota, In: Proceedings of the American Power Conference, 1989, pp. 876-879.
- Palonen, J., *Biomass CFB gasifier connected to a 350 MWth steam boiler fired coal and natural gas – Thermie demonstration project in Lathi in Finland*, Proceedings Biomass Event in Finland, Finland, 1997.

- Palonen, J., Nieminen, E. Berg, *Thermie demonstrates biomass CFB gasifier at Lathi*, Foster Wheeler Energia Oy, Finland, 1998.
- Penninks, F.W.M., *Coal and wood fuel for electricity production: an environmentally sound solution for waste and demolition wood*, nv EPON Power Generation, Zwolle, The Netherlands, 1996.
- Pierik, J.T.G., A.P.W.M. Curvers, *Logistics and pre-treatment of biomass fuels for gasification and combustion*, Netherlands Energy Research Foundation (ECN), Petten, The Netherlands, 1995 (report no. ECN-C—95-038).
- Piscitello, E., C. Demeter, *Biomass cofiring analysis*, The National Renewable Energy Laboratory, 1992.
- Ruiters, *Personal Communication*, Technical Office MTM, Munstergeleen, The Netherlands, 1997.
- Salo, K., H. Keränen, *Biomass IGCC*, Enviropower Inc., Finland; In: Sipilä, K, M. Korhonen, *Power production from Biomass II with special emphasis on Gasification and pyrolysis R&D*, VTT Energy, Espoo, 1996.
- Sten, K., *Personal Communication*, Logset Oy Ab, Espoo, Finland, 1997.
- STORA, *Compendium Slibdroging*, Stichting Toegepast Onderzoek Reiniging Afvalwater (STORA), Den Haag, The Netherlands (in Dutch), 1991.
- Stork Engineering, *The Exergy Steam Drying Process*, Stork Engineering, Goteborg, Sweden, 1996.
- TEKES, *Growing Power; Bioenergy technology from Finland*, TEKES technology development centre Finland, Finland, 1996.
- Unión Fenosa Ingeniería, *Personal Communication*, Unión Fenosa Ingeniería, Madrid, 1998.
- Verbund, *Facts and figures*, Verbund-Elektrizitätserzeugungs-GmbH, Geschäftsstelle Klagenfurt, Klagenfurt, Austria, 1998
(http://www.verbund.co.at/english/service/ber_online.htm).
- Willeboer, W., *The Amer demolition wood gasifier*, N.V. EPZ, Eindhoven, The Netherlands.
- Zamansky, V. M., P.M. Maly, W.R. Seeker, B.A. Folsom, *Biomass fuels in reburning technologies*, 10th European bioenergy conference, Würzburg, 1998.

Annex A Drying technologies

Drying of the forestry and sawdust residues could be necessary for two reasons. The first reason is that the biomass must be stored for a period in which it can start to decompose. The second reason is that the technology used to converse the biomass needs a specific moisture content. For drying biomass materials a range of industrial dryers has been developed: rotary dryers, spray dryers, band dryers, tray dryers, tunnel dryers, fluidised bed dryers, tumble dryers, stenters, drum dryers, pneumatic dryers, infra-red dryers, induction dryers, etc. [Heuvel, 1996]. In this appendix the following biomass drying techniques will be discussed: biological drying, low temperature drying, rotary drum drying, fluidised bed drying, steam drying, fluidised bed drying/steam drying and recompressive drying.

Biological drying of biomass

If biomass has a moisture content of approximately 40% and sufficient organic biological active components, it is possible to dry the biomass by the use of heat originate from biological decomposition of the organic components. By the use of this activity it is possible reduce the moisture content.

In Germany biological drying of residuals from private households has been demonstrated (dry stabilisation). This demonstration consists of a climate system of concrete containers. In this modular designed system the moisture is withdrawn from the residual waste in a natural way with bio heat and set to a value from 40% to <15%. This process takes place in 10 days [Herhof, 1996]. A disadvantage of this method is the use of organic components, and therefore a reduction of the energy output of the system. For every 8.1 kg water that has to be removed the process needs 1 kg (d.m.) of organic material to produce 20 MJ of heat. This means an energy input of 2.5 GJ/twe [Ruiters, 1997]. According to the mentioned experiments the dried waste can be stored in inactive bales.

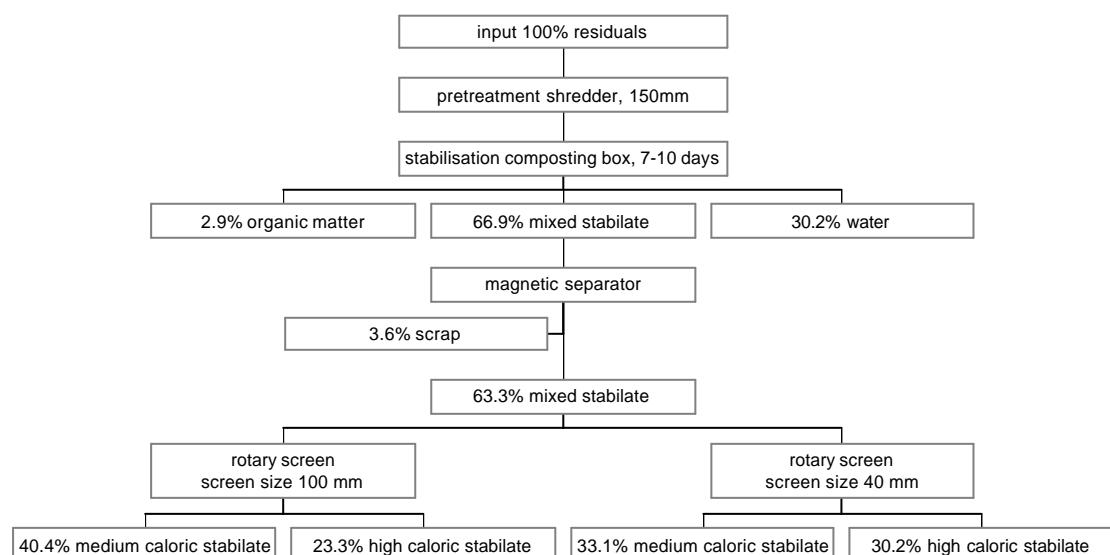


Figure Error! Unknown switch argument. **Dry stabilisation procedure [Herhof, 1996]**.

The cost figures for the dry stabilisation procedure given by MTM are based on a capacity of 90 kton residues. According these cost figures the total costs are 95 Dfl per

ton waste input [MTM, 1997]. **Error! Unknown switch argument.** gives an overview of the different parameters of the dry stabilisation procedure.

Table Error! Unknown switch argument. Cost figures of the dry stabilisation procedure [MTM, 1997].

Capacity (kton)	90
Total area (m^2)	20
Investment costs (million Dfl)	37.4
Operational costs (million Dfl)	8.6
Interest (%)	6.5
Lifetime machinery/electrotechnical installation (year)	10
Lifetime building and others (year)	20
Total costs (Dfl/ton waste input)	95

Biological drying is most suitable for biomass which have a C/N relation of about 20. Domestic waste answers to this relation and will therefore be useful in the dry stabilisation procedure. Wood chips will not answer to this relation, but the chips do have a good structure for the process. Therefore, the wood chips have to be mixed up with other materials, which get going the composting.

Low temperature drying

Drying biomass is possible by the use of waste heat from the combustion process. A technology that makes use of this type of drying is a part of the Whole Tree Energy (WTE) technology. With this technology whole trees are dried in an air-supported double layer plastic/fiberglass dome structure over a 30-day period by using waste heat from the combustion process in the adjacent plant. In this adjacent plant the whole trees are combusted at projected temperatures of 1100 to 1500°C [Lammare, 1994].

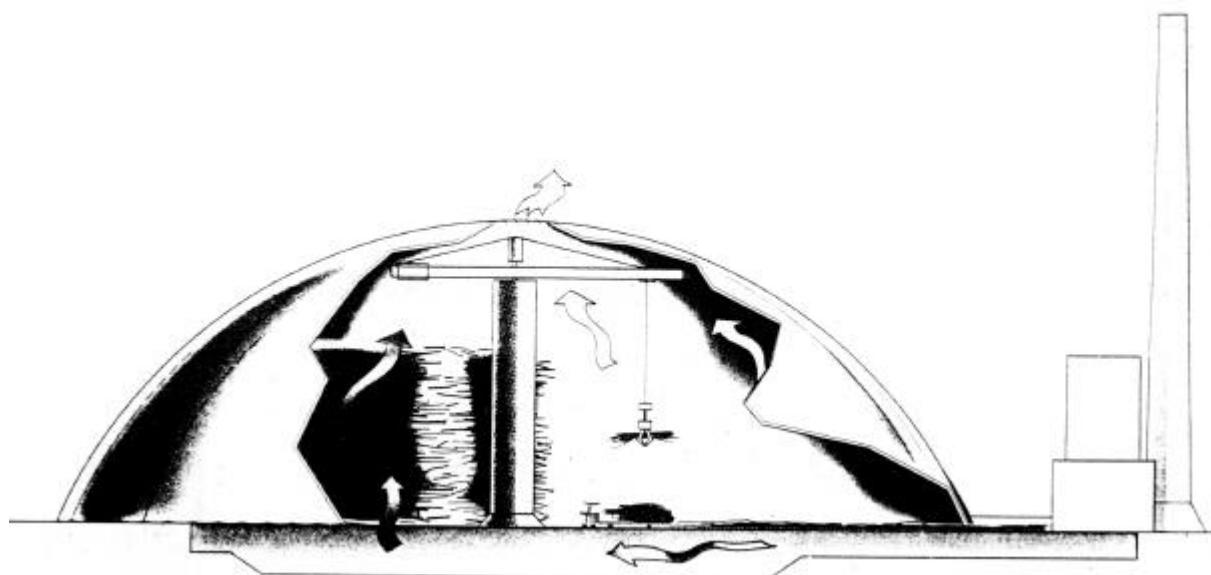


Figure Error! Unknown switch argument. The air supported fiberglass dome used for reducing the moisture content of freshly harvested trees. The trees are

stacked in a circular structure to a height of more than 30 m. Waste heat is piped from the plant into the dome for drying, entering the structure from beneath the tree stack. Low-pressure air separates the inner and outer layer of the double wall cover and acts as an insulation layer [Lammare, 1994].

A test is executed in 1992, which demonstrated the processes of harvesting, transporting, stacking, and drying and combusting whole trees. For the drying tests 3 kton whole trees of 25 centimetres thick are stacked into a square stack about 20 meter on each side and more than 30 meter high. The vertical sides of the chimney-shaped wood stack are wrapped with a tarp. To dry the trees a flue gas flow is generated by combusting propane. This flue gas is led over a heat exchanger to generate a clean air flow of 45 kg/s with a temperature of about 54°C [Ostlie, 1997]. In a 30-day period, the moisture content of the whole trees was reduced from 44% to 20%. Over 700 tons of water were removed from the trees [Lammare, 1994].

A 50 MW_e WTE plant will require an active drying storage area of approximately 5 acres [Ostlie, 1989]. The fibreglass material used for the dome, costing about 50\$₁₉₈₉ per m² of plan area. The dome material is expected to have a lifetime of last about 15 years. To exhaust the warm, saturated exhaust air from the building to the atmosphere, a large circular vent is designed at the top of the dome [Johnston et al., 1992].

According to Johnston the component costs for the drying part of a 100 MW_e Whole Tree Energy plant are 14 M\$₁₉₉₀. The most expensive parts of this concept are the drying building (24% of the total costs), heat exchanger (26%) and the crane (29%). **Error! Unknown switch argument.** gives an overview of the components costs of the 100 MW_e plant.

Table Error! Unknown switch argument. Component costs of the drying part of the 100 MW_e Whole Tree Energy plant [Johnston et al., 1992].

	Costs (M\$ ₁₉₉₀)
Drying building	3.3
Heat exchanger	3.6
Crane	4.0
Tower for crane	0.6
Truck scale	0.1
Drag conveyor	0.5
Front and loaders	0.3
Saw and ram	1.4
Total	13.9

If drying of the biomass stream is necessary then is could be possible to use the air supported fibreglass dome of the WTE concept as starting point for the Narcea I unit. In our case the biomass doesn't consist of whole trees but consists of residues. This can give problems with stacking of the residues in the dome.

Rotary drum drying

The rotary drum dryer is the most conventional and proven technique for drying. In this type of dryer the biomass will be dried by direct contact with hot gas or with indirect contact by hot heated pipes. A disadvantage of the open rotary drum dryer could be the odour problem, but this can be overcome to build a closed system with a indirectly

heated rotary drum dryer [Pierik et al., 1995]. This also eliminates the fire hazard problem.

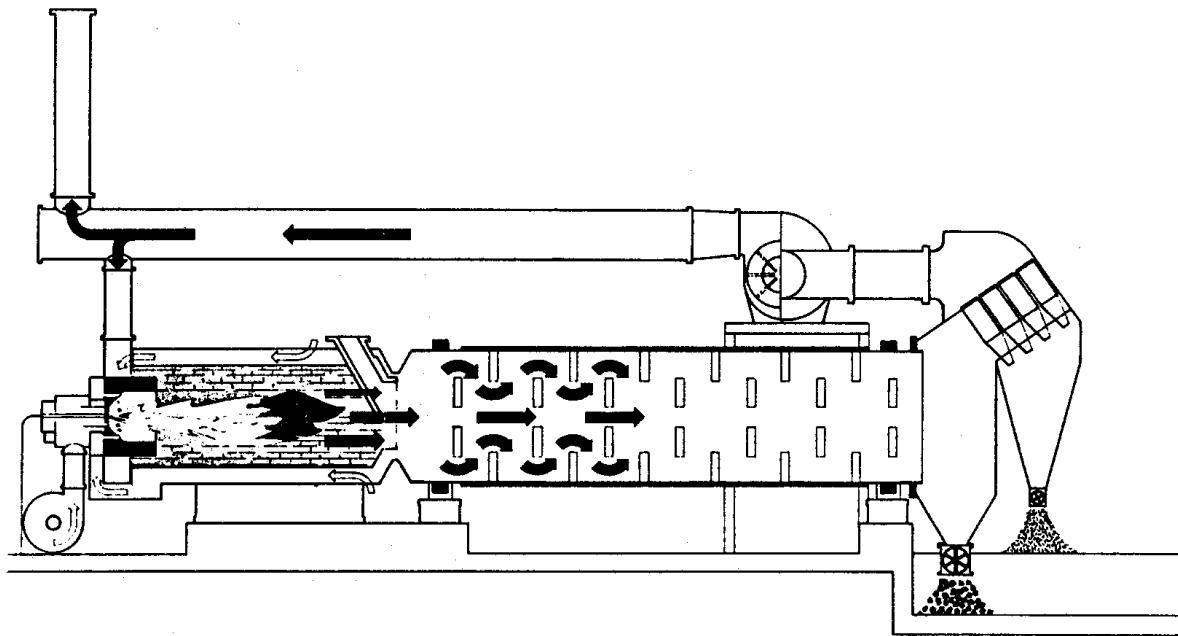


Figure Error! Unknown switch argument. **Example of an open direct heated rotary dryer [Pierik et al., 1995].**

Spectacular improvements in the rotary drum drying technique are not found in this literature survey.

Fluidised bed drying

A fluidised bed dryer consists of a vessel in which the drying medium is blown through a perforated plate, which lies a bed of solid particles. The drying medium flow rate is such that the solids become suspended in the upward flow of the drying medium [Mercer, 1994]. The fluidised bed dryer can be of the open or closed system. Advantages of the closed system are the elimination of the emissions of odour/particles and the elimination of fire or dust explosion hazards. The fluidised gas can be heated before entering the bed or in the bed by way of a heat exchanger. According to STORA the latest concept gives an improvement of the efficiency [STORA, 1991]. Disadvantages of a closed system are the higher investment costs and a more voluminous design by the use of recirculation. When steam is used as heating medium it is possible to work with high pressure steam of 40 bar, which makes it less voluminous than with lower pressure steam [Pierik et al., 1995].

A fluidised bed dryer has been installed by CPC Nederland BV to dry maize (corn) germ, which have a moisture content of 50%. This dryer uses flue gases from a CHP unit, which delivers 138,000 m³ combustion gases per hour at 130°C (70% is used in the dryer). The flue gases are blown into the fluidised bed dryer and are extracted by means of fans, which have a power consumption of 260 kW and will increase the primary energy use.

According to CADDET, the efficiency of the fluidised bed dryer can be improved, because only 18.5% of the total heat content of the combustion gases passing to the bed is used. The investment costs of this dryer were 16 million US dollar and the lifetime

of the installation is expected to be 15 years. The capacity of the dryer is not given by CADDET, but according to them the fluidised bed dryer can be built in a very wide range of sizes [Mercer, 1994].

Steam drying

Two types of steam dryers will be discussed: Exergy Steam Drying Process (formerly: Stork Friesland steam dryer) and Niro steam dryer.

In a Niro steam dryer the heat exchange, drying and product separation are integrated in one single vessel. **Error! Unknown switch argument.** give an impression of the Niro steam dryer. In the vessel steam circulates up to a 16 cell-divided fluid bed placed around the heat exchanger. The wet material is fed into the first cell by a screw conveyor and moved clockwise to cell 16 around the centrally placed heat exchanger. A screw conveyor discharges the dried product from the bottom of cell 16.

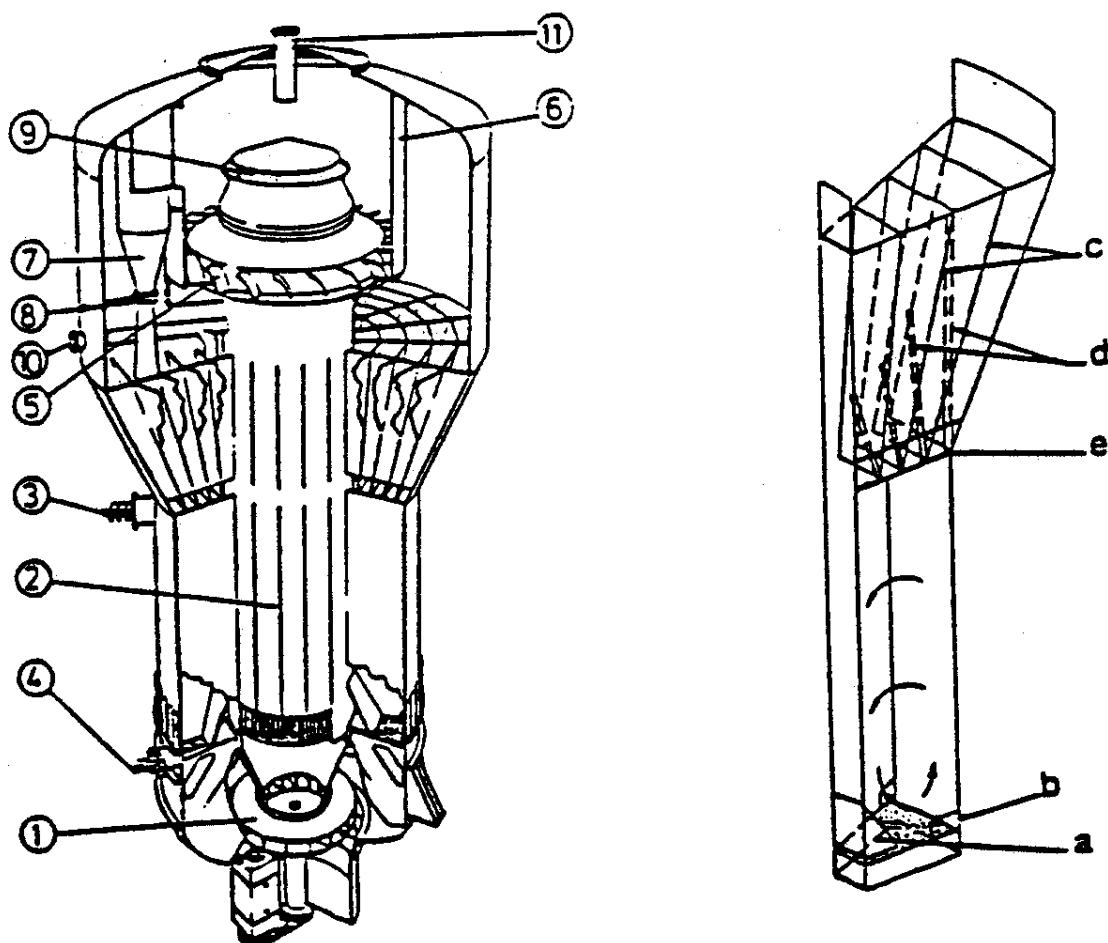


Figure Error! Unknown switch argument. An impression of the Niro Steam dryer [Jensen, 1996].

The drying performance of a Niro steam dryer depends of the pressure of the steam used for drying, as shown in **Error! Unknown switch argument..** For example a Niro steam dryer, built in 1994 in Sweden, evaporates 33 ton water per hour from 80 ton chipped forest waste (a mixture of wood chips, bark and needles from spruce- and pine

trees) per hour [Jensen, 1996]. In the Netherlands the "suiker Unie" has build in 1994 a dryer with a capacity of 40 ton water evaporation per hour to dry beet pulp. It uses steam of 24 bar and 250 °C in the heat exchanger and the steam released of the beet pulp has a temperature of 148 °C and a pressure of 2.5 bar. The total investment costs of this installation are 18 million Dutch guilders (450 kfl/twe/hour). According to Pierik and Curvers the costs of the Niro steam dryer with a capacity of 10 twe/hour is 1.1 mln US Dollar, but these figures are based on a plant built in 1985 [Pierik et al., 1995].

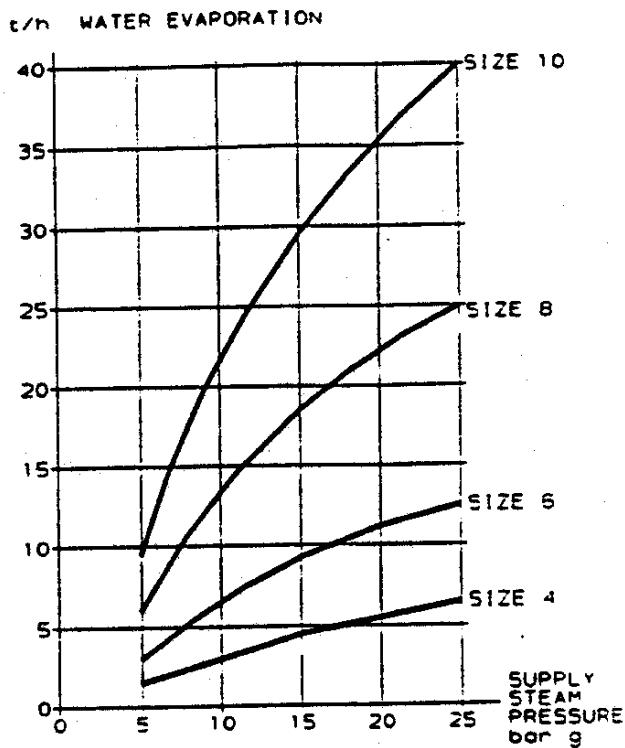


Figure Error! Unknown switch argument. Capacity curves of the Niro Steam dryer (the numbering system represents the diameter in meter of the top of the dryer) [Jensen, 1996].

The Exergy Steam Drying Process manufactured by Stork Engineering has a transport medium consisting of steam and inert gas, that is recirculated in a closed loop (see **Error! Unknown switch argument.**). The wet solids are fed into the flow of pressurised superheated transport steam by means of a pressure tight rotary valve or plug screw. The transport steam and suspended material flow inside the tubes of shell and tube heat exchangers where the transport steam is superheated by medium pressure steam on the shell of the heat exchanger. The used steam is reheated by heat exchangers [Stork Engineering, 1996].

With the use of forest by-products the Exergy Steam Drying has a production of 200 ton by-products per day with an evaporation of 300 ton water per day (12.5 wte/h). These forest by-products have a moisture content of 60 to 70%. The output will have a moisture content of 5 to 20%, with a residence time of approximate 20 seconds [Stork Engineering, 1996]. With this material the heating medium in the heat exchanger has a pressure of 12 bar and the dryer pressure will be 6.5 bar.

The investment costs of the Exergy Steam Dryer with a capacity of 10 twe/hour is 7 mln Dutch guilders (700 kfl/twe/hour) [Voorter, 1995]. According to Stork Engineering it is possible to build a dryer with a capacity of 25 twe/hour for 10 mln Dutch guilders (400 kfl/twe/hour) [Munster, 1997]. Reduction of these costs is possible by simplification of the steam dryer, making use of other materials and by integration of the dryer into the whole system [Munster, 1997].

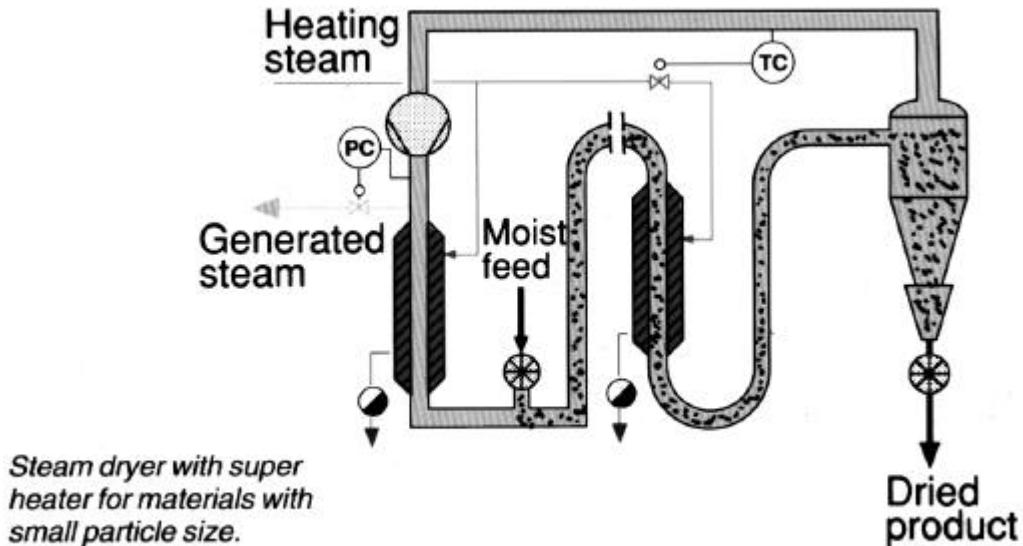


Figure Error! Unknown switch argument. Exergy Steam Drying Process [Stork Engineering, 1996]

The Exergy Steam Dryer and the Niro steam dryer are compared by Vattenfall with the same type of biomass, logging residues including bark and green parts. The moisture content of the biomass was 50% and was dried to a moisture content of 10 to 15 %. According to these tests the mentioned dryers performed well [Salo et al., 1996]. The internal power consumption for the dryer is expected to be 35 to 40 kWh per ton water evaporated [Pierik et al., 1995].

Recompressive drying

All the systems discussed till now have heat losses from the water evaporated from the biomass. A way to recover this kind of heat is with help of a heat pump technique. A drying system based on this principle is called recompressive drying. With this technique the pressure and condensation temperature of the steam are increased by a compressor, and the heat of evaporation is transferred to the drying transport medium through a heat exchanger, as showed in **Error! Unknown switch argument..**

The drying temperature is 70 to 160 °C. Essential point of the heat pumps is the coefficient of performance (COP). Due to a very large temperature difference the COP of the system is very low. The specific investment costs of the system is 485 kfl/twe/h and is in the range of the other drying systems [Pierik et al., 1995].

Stork Engineering has executed their Exergy Steam Drying Process with a recompressive drying in operation. This process has a production of 1000 ton dry peat

per day with an evaporation of 1500 ton water per day. The peat has a moisture content of 55 to 65%. The output will have a moisture content of 10 to 15%, with a residence time of approximate 20 seconds [Stork Engineering, 1996]. With peat and recompressive drying the heating medium in the heat exchanger has a pressure of 14 bar and the dryer pressure will be 4 bar.

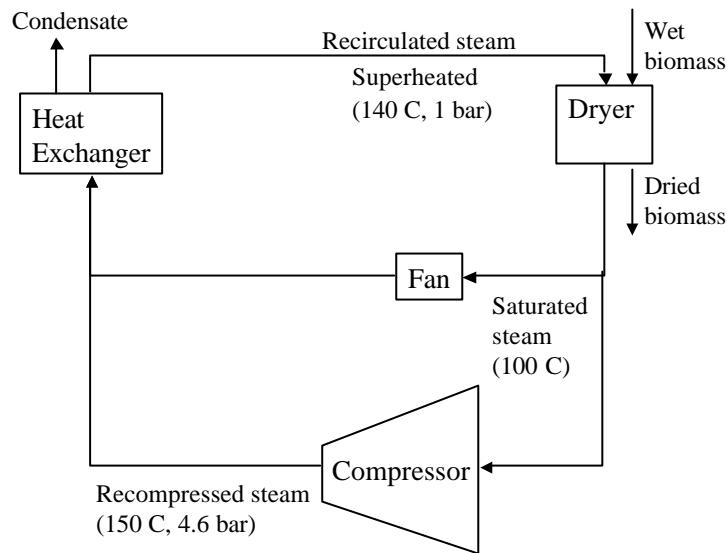


Figure Error! Unknown switch argument. **Process diagram of a drying system with mechanical recompression [Pierik et al., 1995].**

Conclusions drying systems

Biological is a technology which is not suitable for drying only wood chips, since wood chips don't have a right C/N relation to get going the composting. To create that relation the chips have to be mixed up with other residues.

Low temperature drying used in the Whole Tree Energy (WTE) concept could be an option to use the waste heat from the combustion process. According to the tests executed with whole trees the long drying period of 30 days and the surface occupation of the drying dome (for a 50 MW_e WTE plant it needs 5 acres) could be a disadvantages of this system. This drying period could be reduced by the use of forest residues which have a smaller diameter. Also a disadvantage could be the inhomogeneous drying of the whole trees. The total costs of this drying part within the WTE concept are 14 M\$₁₉₉₀.

Error! Unknown switch argument. gives an overview of the investment costs and capacity of the different investigated biomass dryers in a ECN study [Pierik et al., 1995]. This table shows that depending on the type of drying system and the process conditions, a difference in price of a factor 4 is found. The investment costs of all the investigated drying techniques in the ECN study are in the range of 200 to 700 kDutch guilders per ton water evaporation per hour, but these costs figures are based on literature. According to Stork Engineering the cost figures given by ECN for the 12 bar steam dryer are too high. Instead of investment costs of 700 kfl/twe/h given by ECN,

Stork gives cost figures of 400 kfl/twe/h for a steam dryer with a capacity of 25 twe/h [Münster et al., 1997].

Recompressive drying is a technique, which recovers heat losses from the water evaporated from the biomass. With this technique a compressor increases the pressure and condensation temperature of the steam, and the heat of evaporation is transferred to the drying transport medium through a heat exchanger. According to a ECN study this technique has investment costs of 485 kfl/twe/h [Pierik et al., 1995].

A selection criterion for a dryer could be the emission of a system. It could be possible that it is not permitted by law to emit a specific amount of particles, it could be necessary to select a closed system. Advantages of the closed systems are the elimination of the risk of explosion or the risk of fire during drying.

Overall conclusion of the drying techniques is that drying is only necessary if it has been stored for a long period or to achieve a specific moisture content needed for a specific technology. In this appendix the following biomass drying techniques are discussed: biological drying, low temperature drying, rotary drum drying, fluidised bed drying, steam drying, fluidised bed drying/steam drying and recompressive drying. Biological drying can be eliminated because of the misconceived C/N relation of the wood chips. The other technologies are suitable for forest residues. According to the status of the technology it can be concluded that low temperature and recompressive drying are not commercialised. However low temperature drying has perspectives for forest residues.

Table Error! Unknown switch argument. Overview of biomass related dryers.

Drying types	Direct/indirect	Status technology	Energy consumption	Capacity (twe/h)	Specific investment (kfl/twe/h)
Biological	direct (decomposed heat)	demonstration	2.5 GJ/twe	94	400
Low temperature	indirect (flue gas, 54°C)	pilot	-	-	-
Rotary drum	direct (flue gas, 300°C)	commercial	-	18	417
	indirect (steam, 15 bar)	commercial	-	8	375
	direct (flue gas, 180°C)	commercial	-	17	717
Fluidised bed	indirect (steam, 40 bar)	commercial	-	6	417
Steam	indirect (steam, 12 bar)	commercial	-	10	700 ¹
	indirect (steam, 24 bar)	commercial	-	40	450 ²
Recompressive	-	demonstration	-	19	485

¹ Stork Engineering

² Niro

4.3 Modelling & testing

4.3.1 Modelling

4.3.1.1 Colophon

This study is carried out for the EU programme JOR3-CT97-0276 Co-firing of biomass, coal waste and coal in mining sites for electricity generation, as a part of EU Joule III programme. This study was carried out by the department of Science, Technology and Society, of Utrecht University Copernicus Institute.

Authors:

Carlo N Hamelinck

André PC Faaij

ISBN 90-73958-82-2

4.3.1.2 Abstract

The COBIOCOWA project comprises the evaluation of technical and economical feasibility of cofiring biomass with coal on in the pulverised coal fired unit I of the Narcea power plant in Tineo, Asturias, Spain. To research the effects of different cofiring scenarios on plant efficiency and emissions, a computer model has been developed in Aspen Plus. It can estimate effects of cofiring on plant gross and net efficiency and on emissions of NOx, SO2, SO3 and chloride. The model uses continuous relations for pre-treatment energy, reckons with boiler derating effects, and applies combustion relations and partial capture of emissions by the fly ash.

Base case simulation shows that the model is consistent with the existing plant, net plant efficiency is 33.4 % (HHV). Cofiring 5 % sawdust by heating value gives a modest decrease in net plant efficiency to 33.2 %. Cofiring 50 % residues leads to a dramatic power loss, efficiency drops to 26.7 %. Emission levels decrease more or less proportional to the amount of biomass cofired. The model can be used for evaluation of numerous cofiring scenarios and fuel mixes.

Weak spots in the model are mainly related to the fly ash. The influence of fly ash on the heat transfer in superheater and economiser is not modelled, the interaction between fly ash and emissions must be controlled and refined by experiments, and better knowledge of the nature and size of the formed particles allows a more accurate simulation of the cleaning system.

This study yielded necessary information on plant efficiency and emissions. The results will be used to evaluate the economical feasibility of cofiring biomass in the Narcea unit I.

4.3.1.3 Introduction

The objective of the COBIOCOWA project was to determine the technical and economical feasibility of co-firing biomass with coal and coal waste from mining sites, in the pulverised coal fired unit I of the Narcea power plant in Tineo, Asturias, Spain (UFISA 1998). For this purpose Meuleman and Faaij (1998) reviewed state of the art technologies in co-firing biomass with coal and subsequently determined the specific possibilities for the Narcea I unit, to co-fire biomass. It was decided to further research the option of injecting pulverised biomass into the existing boiler, to keep adjustments to the power plant to a minimum. The main objective of the present study is to gain insight in the impacts of co-combusting different fuel combinations at the Narcea I unit in such a configuration.

The main activities consist of:

- Collecting and studying literature on co-combustion biomass with coal, its effects on boiler behaviour, and pre-treatment,
- build a model in Aspen Plus environment,
- discussion with the project partners to incorporate technical details of the plant and results of co-combustion experiments in the model,
- simulation of selected co-combustion schemes.

The power plant has been modelled with the Aspen Plus computer program, so that the actual situation and the planned adjustments can be simulated. Reliable predictions of the overall electrical efficiency, emissions of NO_x, SO_x, fly ash and heavy metals at several co-combustion percentages and fuel moisture contents can be made. The present model of the Group I Narcea power plant:

- Can simulate numerous co-combustion options with different percentages of coal, sawdust, wood residues and coal waste.
- Gives insight in the impact of co-combustion options on the overall electrical efficiency in the power plant.
- Gives insight in the emissions to air of dust, SO_x and NO_x, of simulated options.
- Gives insight in the impact of drying the biomass fuels on the electrical efficiency of the plant.

This report first briefly describes the Aspen Plus simulation program, then in-depth the various units in the plant and how these are modelled, and eventually evaluates two situations of co-combustion:

- 5 % sawdust,
- 50 % wood residues.

The first situation represents a minimal green component in the fuel, this option probably does not need extra sizing equipment and no drastic changes in boiler behaviour are expected, it thus requires a minimal investment. To qualify for the sustainable regime where higher prices are paid for delivered electricity, the plant should produce over 50 % of its power from renewables.

Other studies in this project assessed the availability and nature of biomass resources in the surroundings of the power plant, and their combustion behaviour. Results from these studies are important input parameters to this modelling study.

4.3.2.4 The Aspen Plus simulation program

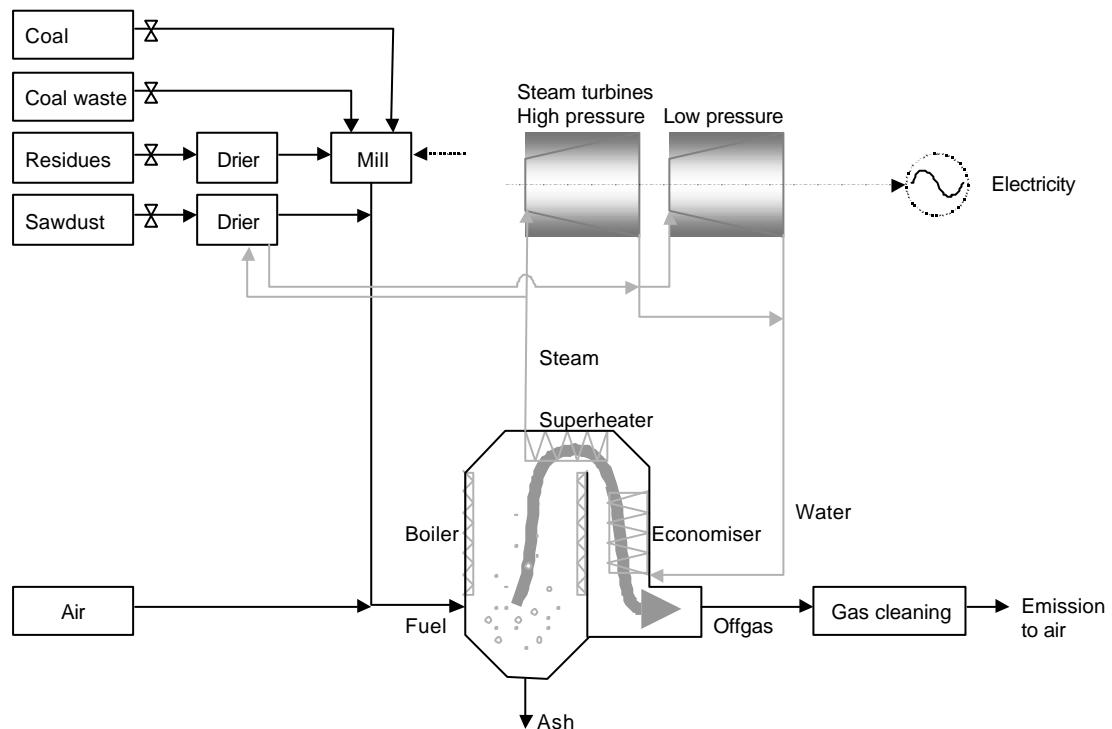
Aspen Plus is a widely used process simulation program. In this program, chemical reactors, pumps, turbines, heat exchanging apparatus, etc are virtually connected by pipelines. Every component is specified in detail: reactions taking place, efficiencies, dimensions of heating surfaces and so on. For given inputs, product streams can be calculated, or one can evaluate the influence of apparatus adjustments on electrical output. The more detailed the data from the real power plant are available, the more accurate the model and thus the results calculated.

The flowsheet of the Group I Narcea power plant model is depicted in **Error! Unknown switch argument..** The complete flowsheet of the model is given in **Error! Unknown switch argument..**, showing from left to right the pre-treatment section, the boiler with heat transfer to the steam cycle, the flue gas cleaning section (only particles removal), and the steam cycle. A fraction of the heat in the steam cycle is used for drying of biomass and some electricity is used for running the plant.

The Aspen Plus model has the following focus points:

- The fuel pre-treatment: size reduction and drying (steam and electricity use)
- The possibility to assess all possible mixtures of the four fuels
- The reactions taking place in the boiler, and resulting NOx and SOx emissions
- Derating of the boiler
- The heat transfer from the boiler to the steam cycle
- The steam cycle turning thermal energy into electricity

Figure Error! Unknown switch argument.. Schematic representation of the modelled power plant.



4.3.1.5 The fuel

The fuels as used for the modelling are characterised in table 1. The values for coal stem from the Union Fenosa ‘Potential report’ (Unión Eléctrica Fenosa 1998), the other values where provided by the University of Oviedo (Sastre et al. 1999; Mahamud 1999).

Table Error! Unknown switch argument.. Composition and heating value of the proposed fuels.

	Coal ¹⁾	Sawdust ²⁾	Wood residues ³⁾	Alternative coal ⁴⁾
Proximate analysis				
Moisture %	9,5	44,0	41	4,5
FC % dry	67,4	14,6	16,5	59,0
VM % dry	5,5 ? 5,0	85,0	83	3,9
Ash % dry	27,2 ? 25,0	0,4	0,5	37,1
Ultimate analysis				
Ash % dry	27,2	0,4	0,5	37,1
Carbon % dry	66,9	48,7	47,6	57,8
Hydrogen % dry	1,8	6,1	6,2	1,3
Nitrogen % dry	1,0	0,1	0,2	0,7
Chlorine % dry	0	0	0	0,02
Sulphur % dry	1,0 ? 1,1	0,02	0,02	0,5
Oxygen % dry	2,1	43,6	45,7	2,0
Heating values				
HHV dry basis kJ/kg	24700	18800	18700	20650
LHV wet basis kJ/kg ⁵⁾	21810 (9,5% wet)	8843 (44% wet)	9367 (41% wet)	19368 (4,5% wet)

¹⁾ Potential Report, actualised fuel data, showing tendencies of decreasing volatile matter and ash, and increasing sulphur.

²⁾ Average of values for sawdust: Chestnut, Eucalyptus, Oak & Pine.

³⁾ Average of values for wood: Chestnut, Eucalyptus & Oak.

⁴⁾ Average of values for high-ash coals and coals without pretreatment: Antisa bulk, G & D bulk, G & D coarse, Gillón coarse and Gillón fine.

⁵⁾ Calculated from the HHV.

The coal presently used at Narcea I is high ash coal, the ash content is 25 - 27 % on a dry basis. For comparison, other PC power plants use coal with less than 10 % ash. The ash content and its distribution within the coal influences ignition stability but despite drawbacks it is not uncommon to satisfactorily fire high ash coal (Skorupska 1993). The Narcea I boiler has been designed for 27 % ash according to the FW Performance sheet in the Potential Report. However it does not seem to be a technical problem to fire low ash coal, as Unit I has been burning coal with 12% ash without problem (Gutierrez Galiano 1999).

The high ash content in the used coal leads to both a lower carbon content (77 % on dry base is quite normal (Robinson et al. 1998)) and HHV (31700 kJ/kg and higher would be more common). In some respect this means that the biomass characteristics come closer to the coal characteristics already used than would be the case in another PC boiler. Therefore cofiring will probably lead to less derating in this case.

The sulphur content of the fuels has not been analysed for inorganic sulphates, iron pyrites and organic sulphur compounds. For preparation processes, information on the relative amounts of the forms of sulphur present is useful for assessing the level to which the total sulphur content of a particular coal might be reduced. Part of the organic sulphur will eventually be trapped in the ash as sulphate; this is depending on the ash properties too.

The potential report gives a characterisation of the sawdust ash. However more important is the ash of the coal, on which no ash analyses has been carried out yet. The composition of mineral matter highly influences the slagging and fouling behaviour. And the amount of carbonates, sulphides and sulphates present in the mineral matter will make an additional contribution to the sulphur and carbon content as has been determined by ultimate analysis, which will, in absence of accurate information, be estimated.

4.3.1.6 Size reduction

The first step in the fuel preparation is size reduction. The maximum particle size for coal is taken 6.35 mm, as suggested in the Technical Description of Narcea Group I (Unión Eléctrica Fenosa 1999). The maximum particle size for biomass is taken 1 mm. Where the Potential Report writes $\frac{1}{4}$ " (6 mm) others report significantly smaller values.

As can be seen in table 2, over 98 % of the sawdust particles is smaller than 1 mm. Further size reduction is not necessary. Size reduction of a small wood residue fraction may be possible in the ball mill, where also the coal is pulverised. For higher biomass fractions a separate mill will be necessary. In Aspen + The existing ball mill is modelled as the cage mill impact breaker type. The mill for wood residues, which is suggested to be of the Hammermill type, is modelled as the multiple roll crusher type.

Table Error! Unknown switch argument.. **Particle size distribution.**

range (mm) lower upper	mass % in this range							
	coal		forest residues		sawdust		coal waste	
	a.r.	milled	a.r.	milled	a.r.	milled	a.r.	milled
0 0,1		2,32		17,4	1,47		2,97	5,57
0,1 0,25		2,03		8,01	20,53		2,97	4,89
0,25 0,315		1,55		5,05	12,46		2,97	4,37
0,315 0,4		2,09		6,11	25,9		1,48	3,29
0,4 0,5		2,92		6,90	21,03		1,85	4,27
0,5 0,63		2,92	0,05	5,97	10,27		1,85	4,20
0,63 0,71		2,31	0,05	4,82	2,69		1,05	2,90
0,71 0,8		3,82	0,2	8,22	2,93		1,06	4,11
0,8 1		8,43	0,3	15,2	1,47		2,49	8,80
1 1,4		14,0	0,4	20,8	0,49		4,31	14,2
1,4 2		20,3	0,4	1,50	0,49		5,38	18,0
2 2,8		15,5	0,7		0,24		5,91	10,9
2,8 3		19,7	1,2				2,46	12,9
3 4		21,0	1,2				6,0	1,56
4 6			15,5					15
6 12,5		1	15,5					42,25
12,5 25			48,2					
25 50			16,3					

The electrical energy for milling biomass in technically sufficient fineness is said to be between 0.5 and 1.5 % of its heating value (Kicherer et al. 1994). Aspen Plus is able to estimate the required work for size reduction. For this calculation the Bond work index or the Hardgrove Grindability Index should be supplied. The Bond work index is a semi-empirical parameter that depends on the properties of the material processed. It is the work required reducing a unit weight from theoretically an infinite size to 80% passing a diameter of 100 micrometers. The Hardgrove Grindability Index (HGI) indicates the difficulty of grinding coal based on physical properties such as hardness, fracture, and

tensile strength. For the coal used at the Narcea Group I the HGI is 55 at a maximum moisture content of 14 % (Unión Eléctrica Fenosa 1999). There is no direct information on the HGI of the wood. The HGI is taken 2.5 at a moisture content of 40 %, with this value the energy needed for milling is 1 % of the heating value.

4.3.1.7 Drying

Cofiring a small fraction of wet biomass should not be a problem, but when cofiring larger fractions it is advised to dry the biomass to 10 % moisture. The biomass drier in the Aspen+ model is based on the Niro steam drier, described by (Pierik and Curvers 1995). The drying process uses about 3000 MJ per tonne water evaporated, delivered by steam at 250 °C and 10 bar. The steam is drawn off the high-pressure steam turbine between 10 and 2.8 bar, which will give a power reduction. The possibility of using steam from the steam cycle has been confirmed by the chef chemist of Narcea (1999). The Niro drier also uses a small amount of electricity: 35 – 40 kWh/twe.

4.3.1.8 Fireplace

4.3.1.8.1 FUEL INJECTION AND BURNOUT

With increasing biomass portion, a slight decrease of carbon burnout could occur. For coarse biomass (Kicherer et al. 1994) report a minimum of 98 % at cofiring 50 %. But it is also written that particles smaller than 3 mm and with moisture contents not exceeding 40% are able to achieve complete burnout (Baxter and Robinson 1999). For best results it is important to keep an oxygen excess. Group I Narcea maintains the oxygen at the economiser exit at 4 % to 8% above stoichiometric (Gutierrez Galiano 1999).

The burnout decreases when coal and biomass are fired in combined burners. (Gast and Visser 1993) advise to use separate burners for biomass and coal. Injection of the powdered wood should be at about the middle row of burners. Injection at the top or bottom of the flame can result in an increasing unburned fraction in fly ash or bottom ash respectively.

In the Technical Description 2.5 % unburned is reported, this value is assumed for the whole cofire range in the Aspen+ model, the unburned char is added to the fly ash. More information on the burnout of the fuels used at the Narcea Group I is expected from Zaragoza University.

4.3.1.8.2 CHEMICAL RELATIONS

Nearly all sulphur in the fuel is oxidised to SO₂ during combustion. Therefore SO₂ emissions in pulverised fuel flames are normally strongly correlated with the sulphur content of the fuel. Based on the biomass sulphur content, a decrease of the SO_x emission is expected. A small fraction of the SO₂ is converted into SO₃ by free radical reactions in the primary flame, the ratio SO₃/SO_x is maximal 1.3 – 2.0 % (Wendt et al. 1973; Skorupska 1993). A substantial part of the SO₃ may be reabsorbed to form sulphates with the alkali metals in the fly ash. Part of the SO₂ also migrates to the fly ash, but the amount depends on the alkaline earth content of the fly ash. A higher alkaline earth content in the fuel, like with miscanthus or straw, results in higher SO₂ capture.

In the Aspen+ model it is assumed that 2 % of the fuel sulphur converts to SO₃ and 98 % to SO₂. All the SO₃ is add to the fly ash and so is 20 % of the SO₂. In the hot flue gas again a small amount of SO₃ is formed due to equilibrium reactions.

Much has been written about NO_x emissions of biomass combustion and cofiring (Skorupska 1993; Sweterlitsch and Brown 1999; Baxter and Robinson 1999, and others). NO_x emissions are only partially related to the nitrogen content of the fuels. The high volatility of the biomass fuel will dramatically lower the NO_x emissions. With other factors, like ignition temperature, fuel oxygen, particle size and fluid mechanics influencing the stoichiometry it is difficult to predict NO_x emissions without test results.

In the computer model all fuel N is used for NO_x formation, all the nitrogen from the air is modelled inert. The distribution of N between NO, NO₂ and N₂O is subject to a chemical equilibrium.

Emission of HCl, CO, CH₄ and other possible reaction products is calculated via equilibria at the combustion temperatures.

4.3.1.8.3 ASH AND FLY ASH [CNHN36]

The ash properties of the fuel mixture are in proportion to the ash properties of the separate fuels (Kicherer et al. 1994). The mineral matter of the fuel is divided over the bottom ash (20 %) and the fly ash (Skorupska 1993). The composition of the fly ash differs from the bottom ash because some elements are more volatile than others are. (Meuleman and Faaij 1997) give a typical distribution of heavy metals over product fractions, as measured in PC boilers burning coal. As written before, unburned carbon and absorbed sulphur adds to the fly ash.

Mercury is a highly volatile compound and stays in the vapour phase. The alternative types of coal contain between 157 and 953 µg mercury per g coal (Mahamud 1999), where common coal contains 0.064 µg/g (Meuleman and Faaij 1997) and between 45 and 139 µg/g cadmium where 0.062 is common. Mercury can be captured from the flue gas when it has adsorbed on fly ash. The mechanism for this adsorption is complex and not fully understood. As nearly all the mercury goes to the flue gas, and only half of this will be recovered, one should anticipate the necessity of a better flue gas cleaning system when burning the alternative coal types. Over 70 % of the cadmium shows up in the flue gas, but almost all will be captured with the fly ash.

The fly ash possibly leads to fouling and slagging. The fouling potential of the biomass part is low to medium, according to the Potential Report. The same report writes that the biomass ash is substantially more alkaline than the ash in the various ranks of coals. Extensive ash deposits can lead to reduced heat transfer, obstruction of the gas flow, corrosion and erosion.

If the particle size distribution of the fly ash is known, the capture efficiency of the cyclone and the electrostatic precipitator can be estimated. For the moment the PSD is modelled with a maximum particle size of 0.4 mm.

4.3.1.8.4 CAPACITY FIREPLACE

Based on the heating value, more biomass than coal is needed for generating the same megawatts. In most power plants this would soon result in derating: For combusting more fuel, more air is needed, this bigger gas flow first causes a decrease in heat transfer and then meets the maximum gas capacity of the boiler. For further augmentation of the biomass fraction the total amount of fuel has to be decreased which results in less steam raising and a lower electricity production. Hence derating.

In the case of Narcea Group I, the high ash content of the coal presently used has two compensating effects. The heating value is already low, for the replacement of coal with wood not much more fuel is needed. And the coal has a very low oxygen content, while the biomass has a high oxygen content.

The gas flow of the base case at 30 tonne/hr coal is taken as a maximum capacity of the fireplace. The base case, while maintaining a 6 % oxygen in the flue gas, gives a gas stream of 261 tonne per hour, or $9.24 \cdot 10^5 \text{ m}^3$.

4.3.1.8.5 BOILER EFFICIENCY

The boiler efficiency depends on how well the combustion heat can be transferred to the steam cycle. It is a function of the gas velocity as well as the construction of the installation. In the Technical Description, the boiler efficiency is reported to be 86.37 on HHV basis. In the modelled base case with 30 tonne per hour coal input (186.3 MW_{th}) 236.2 tonne steam per hour is raised from 209 °C to 525 °C, which means a boiler efficiency of 89.9 %.

4.3.1.9 Steam cycle

With the heat transferred in the boiler, superheater and economiser, water is turned into steam. The steam conditions 525°C and 92 kg/cm² have always to be met, but the flow of course is dependent of the amount of heat. The input water conditions are 209 °C and 98 kg/cm². The total pressure drop through economiser-boiler-superheater is 6 kg/cm² and it is supposed that the superheater part takes the biggest share, therefore the pressure drops in the boiler and economiser are both estimated 1 kg/cm², while 4 kg/cm² for the superheater. Aspen + adjusts the water input to the economiser in such way that the superheater outlet conditions are met. In the modelled base case of 30 tonne coal/hr 236 tonne steam/hr is produced, this is the same as written in the Technical Description.

The model of the steam cycle is based on the second flow sheet that was provided by the plant service manager (Gutierrez Galiano 1999). The steam is expanded to 22, 9.8 and 2.74 kg/cm² in a high-pressure turbine and to 1.33, 0.46 and 0.05 kg/cm² in two parallel low-pressure steam turbines. The heat of the higher branches is recovered in heat exchangers so that the water input to the boiler is continually 209 °C. For all Aspen + calculations concerning the steam raising and expansion the STEAM-TA property method was used.

In the modelled base case the steam turbines together produce 61.5 MW_e, the Technical Description writes 63 MW_e, while empirical data from Narcea Group I vary between 57 and 62 MW_e. The efficiency of the steam cycle should depend on the load and have an optimum at the design steam flow. However this could not be concluded from the provided data.

4.3.1.10 Researched cases

Error! Unknown switch argument. summarises the researched scenarios. The base case of the plant is simulated in order to check the consistency of the model with the existing plant. Scenario 1 comprises a modest co-firing of sawdust, only requesting marginal adaptations to the plant and expected to give a small drop in plant efficiency. To compensate for the lower ash content of this fuel mix (see Section 3), also a Scenario 1b has been studied where part of the coal is replaced by high ash coal waste. Scenario 2 examines the co-firing of 50 % biomass in the form of wood residues; it will not be possible to supply such a large amount of sawdust. Wood residues need a size reduction installation and co-firing 50 % biomass is expected to give a large drop in plant efficiency. The outcomes of the different scenarios are discussed hereafter.

Table Error! Unknown switch argument.. Scenarios studied with the Aspen Plus model.

	coal	coal waste	sawdust	wood residues
Scenario 0	100 %	-	-	-
Scenario 1a	95 %	-	5 %	-
Scenario 1b	95%		5 %	
Scenario 2a	50 %	-	-	50 %
Scenario 2b	50 %		-	50 %

4.3.1.10.1 100 % COAL

30 tonne coal/hr is the base case. The coal has a total higher heating value of 186.3 MW_{th}. In the model combustion of this fuel gives $9.24 \cdot 10^5$ m³/hr gas through superheater, which will be taken as maximum boiler capacity. With the combustion heat 236.2 tonne/hr steam is raised, i.e. 167.6 MW_{th}, the boiler efficiency is 89.9 %, where the potential report writes 86.4 %. The generated power is 61.7 MW_e, i.e. a steam cycle efficiency of 36.8 %, this is a little higher than the real steam cycle efficiency reported for Narcea Group I: 33.5 – 36.6 % (Alonso González 1999). With the electricity for mills and pumps subtracted the plant delivers 60.7 MW_e, the overall efficiency is 32.6 % by higher heating value.

After particle removal, the flue gas contains 0.2 % NO, and 9 ppm NO₂. SO₂ and SO₃ levels are 500 and 9 ppm respectively.

4.3.1.10.2 5 % SAWDUST BY HHV

When cofiring 5 % sawdust by HHV, initially 1.5 tonne/hr coal is replaced with 3.18 tonne/hr sawdust. The gas volume at the economiser exit grows slightly to $9.30 \cdot 10^5$ m³/hr. To correct for this the input of biomass and coal is decreased with 0.6 %. Now 234.4 tonne/hr steam can be raised, of which some is used in the biomass dryer. Of the 61.0 MW_e generated, 1.5 MW_e is used for drying, which leaves a plant output of 59.5 MW_e. The plant efficiency is 32.2 % by higher heating value. This means a net plant power loss of 1.2 MW_e that somehow has to be generated elsewhere. 1.2 MW_e equals

0.6 tonne coal in the Narcea I unit, so that the effective decrease in coal use is only 1.1 tonne coal. The CO₂ reduction of cofiring 5 % sawdust is thus 3.7 %.

The NO₂, SO₂ and SO₃ levels show a decrease of about 5 % compared to the base case.

Substitution of coal by biomass leads to a lower total ash content 21.5 % instead of 22.6 %. This could be compensated by substituting another 9% of the coal with the alternative high ash coal. After correction for the boiler capacity the input is 25.6 tonne/hr coal, 3.17 tonne/hr sawdust and 3.04 tonne/hr coal waste, which gives a total heat input of 185.2 MW_{th}. In the boiler 234.6 tonne/hr steam is raised, which results in 61.0 MW_e of generated power. The plant output is 59.5 MW_e.

The NO_x and SO_x levels in the flue gas are comparable to the 5 % sawdust case, but an emission of 52 ppm HCl shows up.

4.3.1.10.3 50 % WOOD RESIDUES BY HHV

To cofire 50 % wood residues by HHV, 15.0 tonne/hr coal is replaced with 30.4 tonne/hr wood residues. This gives 9.49·10⁵ m³/hr gas through at the economiser exit. To adjust the flue gas flow to the boiler capacity, the fuel input is decreased to 181.3 MW_{th}. With this per hour 224.9 tonne steam is produced. For drying the wood residues almost 9 MW_{th} is required, which leaves a net 48.4 MW_e of electricity to be generated. The overall efficiency by higher heating value is low: 26.7 %. This means a net plant power loss of 13.3 MW_e, equalling 6.5 tonne coal in the Narcea I unit. The effective decrease in coal use is 8.9 tonne coal. The CO₂ reduction of cofiring 50 % is thus 29.8 %.

NO_x and SO_x emission levels decrease proportionally.

At 50 % wood residues by heat the decrease in ash is dramatic, it falls to 11.5 %. Compensation with coal waste is only possible by making use of Gillon Coarse (53.1 % ash) in a fuel composition of 10.3 % coal, 39.7 % coal waste and 50 % wood residues. As more fly ash is produced, the flue gas volume is relatively smaller per heat input, which leads to a potentially higher steam and electricity production and higher plant efficiency (27.1 %). This result has to be interpreted with caution; the high fly ash load leads to a decrease in heat transfer, which is not modelled.

The results are summarised in **Error! Unknown switch argument.** and **Error! Unknown switch argument..**

Table Error! Unknown switch argument.. Partial and overall efficiencies for different fuel input combinations.

	100 % coal	5 % sawdust by HHV	50 % wood residues by HHV
Fuel input tonne/hr	coal: 30	coal: 28.3 sawdust: 3.16	coal: 14.6 wood residues: 29.6
HHV input MW _{th}	186.3	185.0	181.3
LHV input MW _{th}	181.8	179.2	165.5
Steam raised	236.2	234.4	224.9

	tonne/hr		
Steam raised MW _{th}	167.6	166.2	159.5
Boiler efficiency	89.9 %	89.9 %	88.0 %
Generated power	61.7	61.0	50.2
MW _e			
Steam cycle efficiency	36.8 %	36.7 %	31.5 %
Plant output MW _e	60.7	59.5	48.4
Overall HHV efficiency	32.6 %	32.2 %	26.7 %
Overall LHV efficiency	33.4 %	33.2 %	29.2 %

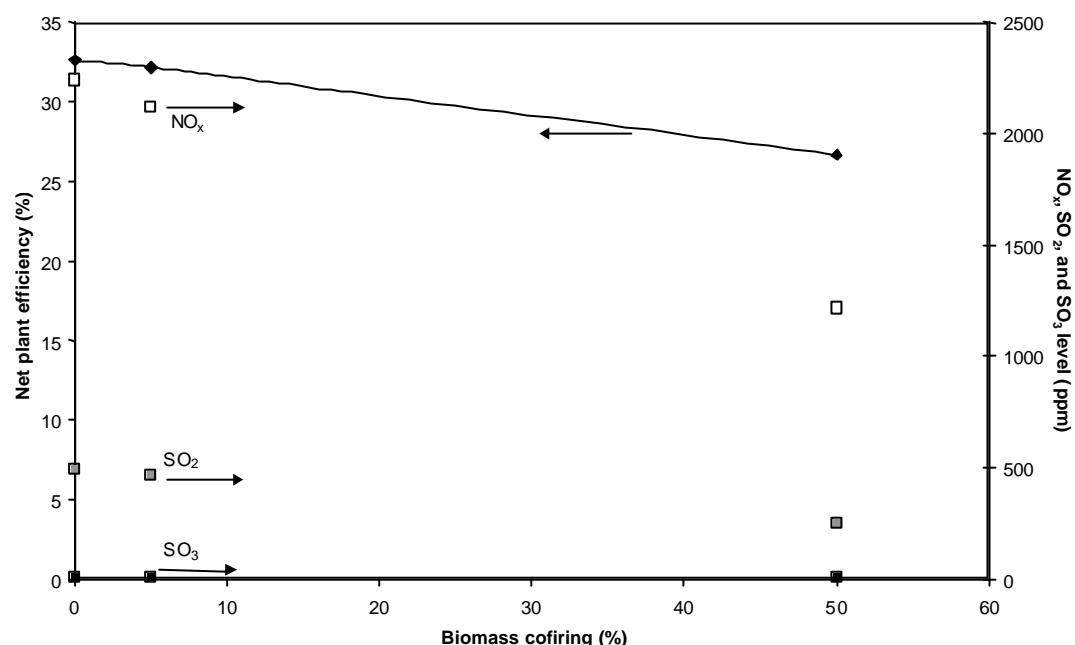


Figure Error! Unknown switch argument.. **Net plant efficiency and emission levels for different biomass cofiring scenarios.**

4.3.1.11 Conclusion

To evaluate cofiring biomass with coal scenarios for the Narcea I unit, a computer model has been developed in Aspen Plus. It can estimate effects of cofiring on plant efficiency and on emission of NO_x, SO_x and chloride, by using continuous relations for pre-treatment energy, accounting for derating of the boiler, applying combustion relations and partial SO_x capture by the fly ash.

With the computer model two cofiring cases have been studied. Cofiring 5 % sawdust by heating value gives a modest decrease in net plant efficiency: 33.2 % HHV versus 33.4 % for the present 100 % coal base case, and leads to a net CO₂ reduction (power loss compensated) of 3.7 %. Emissions of SO_x and NO_x are reduced by 5 %. Cofiring 50 % wood residues gives a dramatic power loss, the efficiency drops to 26.7 % (HHV), and the net CO₂ reduction is only 30 %. Emission levels reduce proportionally to the amount of biomass cofired.

For the present study the fuel compositions of the different types of sawdust, wood residues, and alternative coals have been averaged. The model can make calculations on all the extremes within fuel compositions. These calculations are important for the economic evaluation of the co-combustion options, by Unión Fenosa.

A weak spot in the model is the particle removal system. Also the cleaning system itself has to be studied more closely before accurate modelling is possible. Not included in the model is the ash composition. With detailed information on the ash composition of the different fuels however, it should be possible to estimate compositions of bottom and fly ash. The influence of fly ash on the heat transfer in superheater and economiser is not modelled.

Practical results from Zaragoza experiments give the opportunity to both verify and extend the model. Model calculations at Zaragoza revealed that NO_x emissions decreased with decreasing oxygen excess: 9 – 31 % reduction at cofiring 20 % biomass and 3 – 5 % excess oxygen. However, in order to keep the unburned fraction low (5 – 7 %), it is necessary to fire smaller biomass particles (1 – 1.4 mm). It therefore appears that to maintain the maximally 2.5 % unburned, the biomass particles should even be smaller than 1 mm. Co-firing experiments can fine-tune relations for the emissions and its interaction with the fly ash.

This study yielded necessary information on plant efficiency and resulting emissions. The results will be used in other studies of the COBIOCOWA project. Finally the plant economy in the different co-firing scenarios will be calculated by evaluating the required hardware investments and the fuel costs.

4.3.1.12 Literature

- Alonso González J, 1999, personal communication, Unión Fenosa Ingenieria, Madrid.
- Baxter L and Robinson A, 1999, Cofiring biomass with coal, in proceedings of Fourth Biomass Conference of the Americas, Oakland.
- Gast CH and Visser JG, 1993, Combustion experiments using pulverised wood/pulverised coal in the 1 MWth testboiler (in Dutch), Kema, Arnhem.
- Gutierrez Galiano L, 1999, personal communication Narcea Power Station, August - December 1999.
- Kicherer A, Gerhardt T, Spliethoff H and Hein KRG, 1994, Co-combustion of biomass/sewage sludge with hard coal in a pulverized fuel semi-industrial test rig, in: Bemtgen JM, Hein KRG and Minchener AJ (eds.), Co-combustion of biomass/sewage sludge and coals, University of Stuttgart, Stuttgart.
- Mahamud M, 1999, personal communication, University of Oviedo, Department of Chemical and Environmental Engineering, Oviedo.
- Meuleman B and Faaij A, 1997, Het gedrag van zware metalen in kolencentrales en afvalverbrandingsinstallaties, Science, Technology and Society, Utrecht University, Utrecht.
- Meuleman B and Faaij APC, 1998, Technology assessment for unit I of the Narcea Power Station in Spain, Utrecht University/Science Technology and Society, Utrecht, the Netherlands, 51 pp + annexes.
- Pierik JTG and Curvers APWM, 1995, Logistics and pretreatment of biomass fuels for gasification and combustion, Netherlands Energy Research Foundation ECN, Petten.
- Robinson AL, Junker H, Buckley SG, Sclippa G and Baxter LL, 1998, Interactions between coal and biomass when cofiring, in proceedings of Twenty-Seventh Symposium (International) on Combustion, Boulder.
- Sastre H, Mahamud M, Fuentes LF and González N, 1999, COBIOCOWA Fuel Characterisation Report, University of Oviedo, Department of Chemical and Environmental Engineering, Oviedo.
- Skorupska NM, 1993, Coal specifications - impact on power station performance, IEA Coal Research, London, 122 pp.
- Sweterlitsch JJ and Brown RC, 1999, NO_x emissions reduction: an application of biomass reburning technology, in proceedings of Fourth Biomass Conference of the Americas, Oakland.

UFISA, 1998, Project programme JOR3-CT97-0276 Co-firing of biomass coal waste and coal in mining sites for electricity generation (COBIOCOWA), Union Fenosa Ingenieria, Madrid, Spain, 16 pp.

Unión Eléctrica Fenosa, 1998, Potential of Group I Narcea power plant for Cofiring Biomass.

Unión Eléctrica Fenosa, 1999, Technical Description Group I. Narcea power plant.

Wendt JOL, Sternling CV and Matovich MA, 1973, Reduction of sulfur trioxide and nitrogen oxides by secondary fuel injection, in proceedings of Fourteenth Symposium (International) on Combustion, Pittsburgh.

Aspen Plus model flowsheet

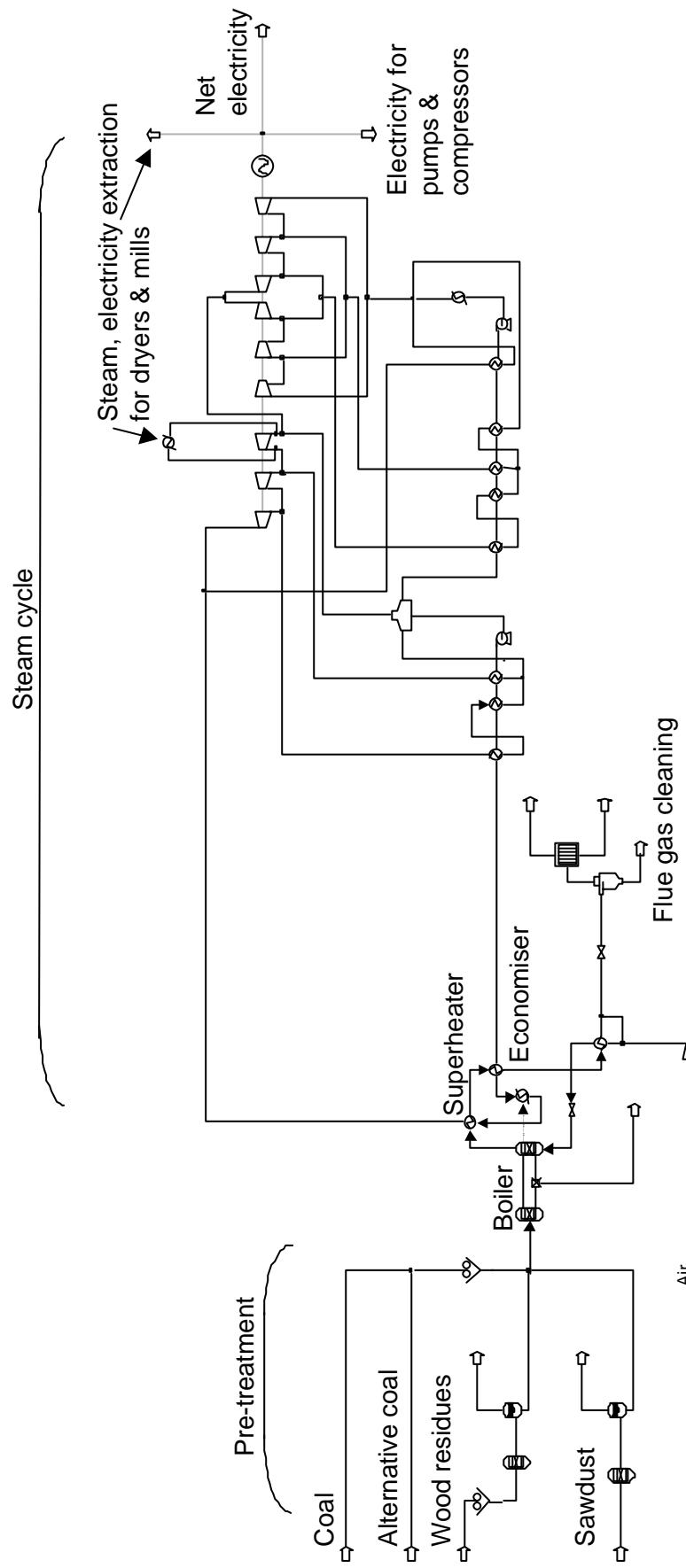


Figure A-1. Aspen Plus flowsheet of the modelled Group I Narcea power plant. From left to right are shown the pre-treatment section, the boiler w

4.3.2 Lab scale test and test in a semi-industrial furnace

4.3.2.1 Background and motivation

It is generally accepted that cofiring is one of the most advantageous alternatives for the production of energy from biomass or other alternative fuels. Since it takes advantage of existing high-efficiency boilers and steam-cycles, it is considered a short-term, low-cost option, providing a significantly higher efficiency than the traditional fixed-bed furnaces.

However, a very limited use of this option has been done. A plausible explanation is that the burning of new fuels in existing large facilities entails the risk of serious operating problems in the whole plant due to ill-designed cofiring strategies and/or a wrong choice of the alternative fuel or its pre-treatment. As a result, in many cases the technological solution adopted is combustion on grate or other similar systems, considered as a less risky option. This situation (or even some legislations that support economically the energy generated by dedicated systems but not from cofiring) is in clear contrast with the criteria to attain a sustainable development (e.g., maximum efficiency or minimum emissions) that should drive the exploitation of renewable energy sources.

The project *Cobiocowa* is an attempt to develop a systematic and rational feasibility analysis of the implementation of cofiring in an existing pf boiler. The UZ subproject is centred in the study of combustion characteristics of the current and new fuels. The approach proposed and followed here is intended to obtain a detailed knowledge of the behaviour of the fuels under the actual combustion conditions prevailing in the real system, so that it can be used as a valuable information to develop a reliable design of the cofiring strategies considered.

4.3.2.2 Methodology employed

Two complementary activities have been planned:

1. Characterisation of biomass as a fuel (lab-scale tests)
2. Study of different cofiring strategies (semi-industrial tests)

The first stage addresses the calculation of the parameters that characterise each of the materials tested. The experimental method is based on the burning of the pulverised fuels

in an Entrained Flow Reactor, which provides a combustion environment that simulates the conditions inside full-size pf boilers. In fact, this is considered the most reliable testing method for the analysis of pf combustion systems. The testing procedure has been designed to obtain the values of the *Frequency Factor* and the *Activation Energy*, which are the universal parameters that describe the combustion behaviour of a particular fuel. This approach allows predicting the combustion rate for any temperature, oxygen concentration or particle size.

The performance of specific cofiring configurations is evaluated in the second stage. In the semi-industrial trials, the results are not only influenced by the properties of the fuels but also by the particular geometry and operating conditions. Therefore, these tests provide the required insight into the potential and the limitations of the different cofiring options. The combustion facility is a semi-industrial furnace, large enough to reproduce the combustion characteristics of real systems and, at the same time, featuring a broad flexibility and a complete instrumentation to simulate different strategies and to yield a detailed characterisation of the process.

The information obtained in the lab-scale tests is used to design the trials to be conducted in the furnace. On the other hand, the knowledge gained at semi-industrial scale makes it possible to propose a pre-design of the retrofitting of a full-size pf boiler, and is also utilised by other partners for the evaluation of the performance of the process as a whole.

During the course of the project, a permanent revision of scientific and technological databases has been conducted, in order to take advantage of the advances in this subject, mainly in the UE and USA.

4.3.2.3Results obtained and key findings of the work

From a global viewpoint, the authors consider that the tasks and objectives contemplated within the contribution of UZ have been amply covered.

The following sections are a summary of the results obtained in the different stages of the project.

Apart from the complete database obtained in this project, a valuable result of the project is the development and utilisation of a systematic method for the analysis and design of cofiring strategies. The approach followed here is considered a rational procedure that combines experimental methods to provide a realistic characterisation of the performance

of different combustion methods with the final objective of their implementation in practical systems.

4.3.2.3.1 Lab-scale tests

One of the main objectives of the present study is the detailed knowledge of the behaviour as a fuel of the solid materials considered, as the most rational means to design a suitable cofiring strategy.

The approach adopted in the present work is based on the determination of the ‘universal’ kinetic parameters that characterise the heterogeneous oxidation rate of a solid material.

The procedure for the characterisation of a solid fuel involves mainly two stages:

1. Experimental determination of the combustion rate of the fuel. An Entrained-Flow Reactor (Figure 1) has been used for the determination of the combustion curves (i.e., degree of combustion along the time) for the different fuels. A specific test program has been conducted for each of the materials, providing the data necessary to achieve a complete characterisation.
2. Calculation of the values of the kinetic parameters that represent the combustion behaviour of the fuels considered. A specific code for the simulation of the evolution of burning particles has been developed and used. The only unknowns in this code are the kinetic parameters, which depend on the particular fuel considered, and are inferred from the experimental results. As a result, the two kinetic parameters (frequency factor, A , and activation energy, E_a) characterising the different fuels are obtained.

Another relevant experimental result of the tests is the “high-temperature volatile yield”; i.e., the fraction of fuel released in gaseous form when the particles are subject to heating-rates and temperatures representative of those found in practical furnaces.

Table 1.1 summarises the results obtained for the five fuels tested. Besides the biomasses, two different types of coals have been studied:

- Anthracite A: Standard coal, representative of the average anthracite customarily burnt in Narcea power plant.
- Anthracite B (very high ash content). The fraction of non-combustible matter is higher

than the value admitted in the normal operation of the plant. Therefore, this coal is representative of mining residues, currently rejected, that could be exploited if a suitable cofiring strategy is found.

Table 1.1 – Combustion parameters of the fuels

	Anthr. A	Anthr. B	Oak sawdust	Chestnut tree sawdust	Eucalyptus sawdust
A ($\text{kg/m}^2/\text{s/Pa}^{0.5}$)	2.6×10^{-3}	3.3×10^{-4}	1.3×10^{-2}	0.1	0.1
E_a (kJ/mol)	45	80	45	65	65
High-T volatile (% by wgt)	7.52	6	92.47	92.15	92.63

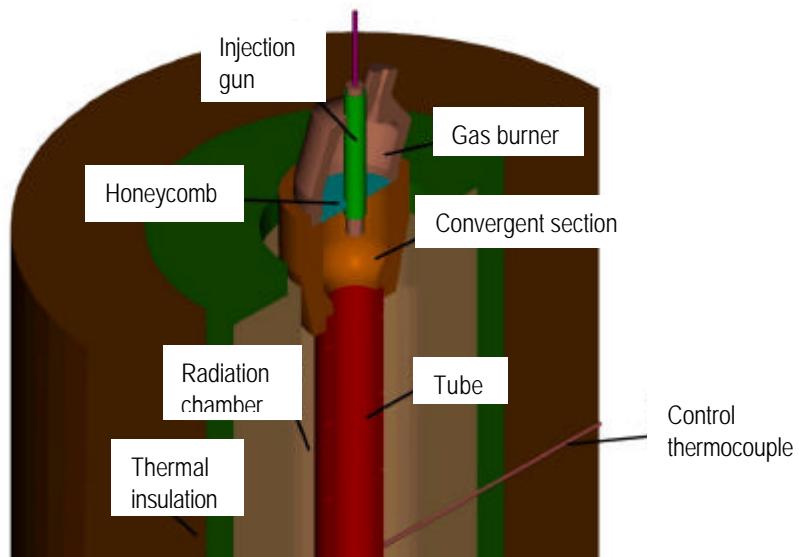


Figure 1 – Upper section of the EFR and injection systems.

4.3.2.3.2 Semi-industrial tests

Two different strategies have been considered as potential candidates for the implementation of cofiring in the Narcea power plant:

1. Combustion of coal/biomass blends. That requires selecting a method to obtain a mixture of both fuels, and then injecting the blend using the existing burners. An advantage of this option is that the boiler does not need to be modified, and the only investment required is the system for biomass feeding and its blending with coal.
2. Separate injection of biomass. In this case, the coal injection system remains unmodified, and specific ports must be opened in the furnace walls for the injection of the new fuel. Among the many possibilities, the implementation of a reburning configuration was selected as a promising option that, besides a high combustion efficiency, could lead to significant reductions in NOx emissions.

A semi-industrial furnace has been used to evaluate the performance of different cofiring scenarios (Figure 2). The combustion chamber and ancillaries available afford the flexibility required to implement the configurations selected. A solids-feeding system that has been designed and constructed within this project is used to inject the biomass either blended with the coal or at selected locations along the furnace. The facility is fully instrumented, so that a thorough characterisation of the process can be obtained.

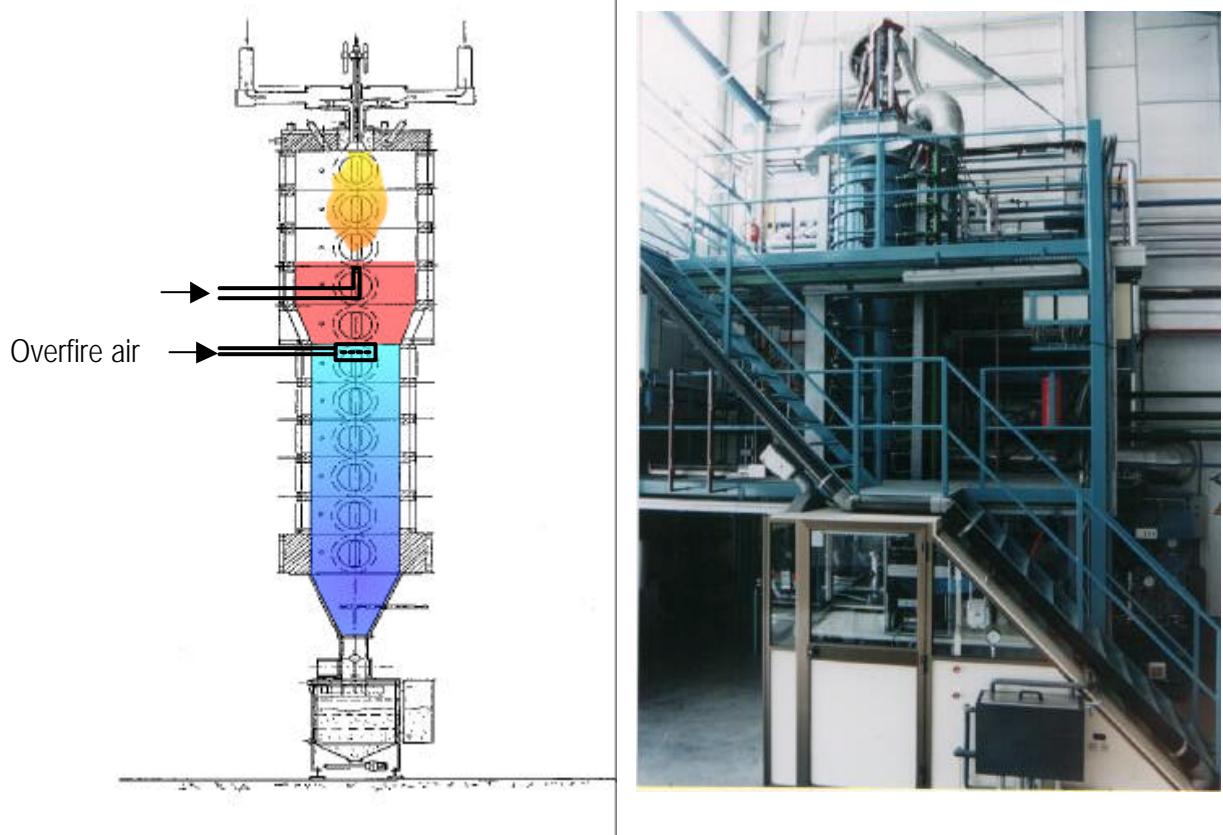


Figure 2 – Dimensions and general view of the semi-industrial furnace

Some global conclusions on the performance of the cofiring strategies tested are:

- Combustion of coal/biomass blends:
 - The emissions of unburnt matter (CO and carbon-in-ash) is even lower than in the baseline test (i.e., only anthracite). Also, visual inspection of the flame indicates that a more intense and stable combustion is achieved when biomass is injected. Therefore, from the viewpoint of combustion efficiency, cofiring using a coal/biomass blend can have some advantages. This is especially true for coals with very low volatile-content, characterised by a slow-combustion and, therefore, with difficulties to achieve low carbon-in-ash values.
 - SO₂ emissions are gradually reduced as the amount of biomass increases. The measurements are consistent with the reduced input of sulphur into the combustion chamber, and no additional decreases attributable to interactions with biomass ashes have been detected.
 - NOx emissions do not change appreciable with respect to the baseline case. The tests performed display different trends depending on the particle size of the

biomass. A more detailed study of this effect could be useful in order to minimise NOx emissions based on an adequate control of the combustion rate of biomass.

- Use of biomass as a reburn fuel:

- A detailed characterisation of the flow inside the combustion chamber has been performed in order to gain some insight into the reburning process. The experimental programme has also included one test using natural gas, so that the results with biomass can be related to the well-documented case of reburning using natural gas. Regarding the efficiency of biomass as a reburn fuel, the tests indicate that it has a very good potential, with a NOx-reduction rate slightly lower than natural gas (60% with biomass vs. 74% with natural gas).
 - No significant variations in the emissions of unburnt matter (CO and carbon-in-ash) have been detected in the reburning tests compared to the baseline case. This aspect is, probably, the main potential drawback of the reburning technique, as it causes a reduction in the effective oxidation time of the fuel. The tests performed, however, indicate that reburning can be implemented without decreasing the combustion efficiency.
 - The influence of important parameters, such as the amount of biomass or the stoichiometric ratio in the primary flame, has been quantified. NOx reductions exceeding 50% have been measured in the most favourable case (lowest excess oxygen from the primary flame, and highest amount of biomass). The results obtained can be used to predict the emissions within a wide range of operating conditions.

4.3.2.3.3 Analysis of the implementation in Narcea-I

The group I of Narcea power plant is the facility selected for the assessment of the feasibility of a biomass cofiring implementation. Even though full-scale trial could not be performed due to some external constraints, a detailed analysis of the plant has been performed in order to select the most convenient combustion strategies.

According to the results obtained in the semi-industrial furnace, the reburning technique was selected as it is expected to provide the better results. Also, the geometry of the Narcea-I furnace (arch-fired) is particularly suitable for this combustion strategy. Figure 3 is a schematic of the furnace, indicating the injection ports for biomass and overfire air.

A number of conditions were predefined in a hypothetical retrofitting of the plant:

- An amount of biomass equivalent to 20% of total thermal input was selected as the target cofiring rate.
- Oak wood is selected as the biomass fuel.
- The biomass should be injected on the walls of the central chimney.
- The excess oxygen in the flue gases is set at 5% by vol.
- The unburnt fraction of the biomass should be similar to the nominal value in the current coal-fired plant (i.e., around 5%).
- Overfire-air ports are installed 3.5 m downstream the biomass injectors.

The mass-flow rates of the fuels (coal and biomass) and air streams (primary flame, biomass transport gas, overfire air) need still to be defined, as well as the maximum particle size of the biomass.

In the first place, a sensitivity analysis of the influence of NOx reduction on the nature of the biomass transport gas is performed using the information obtained in the semi-industrial furnace. Flue gas recirculation (FGR), with $[O_2]=5\%$ is selected.

In the second place, a number of scenarios are analysed. For different mass-flow rates of the fuels and air streams, the expected results are analysed:

- NOx emissions: The database obtained in the semi-industrial tests is used to predict the NOx reduction obtained with the different flow rates (i.e., different values of stoichiometric ratio in the reburning zone).
- Unburnt solids: The particle combustion code is used to simulate the evolution of the coal and biomass particles, in order to estimate the unburnt fraction remaining at the

exit of the furnace. As a result, the maximum particle size of the biomass is calculated.

Table 1.2 summarises the main results for some selected cofiring scenarios in the real plant. The performance is evaluated in terms of NOx emission (% reduction compared to baseline case) and unburnt fuel (baseline value is 5%).

Table 1.2 – Cofiring scenarios in Narcea-I (reburning technique)

	Scenario B	Scenario C	Scenario D
Coal (ton/h)	23.93	23.93	23.93
Air in 1ry zone (ton/h)	253.36	238.57	225.43
Biomass (ton/h)	10.6	10.6	10.6
FGR (ton/h)	10.6	10.6	10.6
Overfire air (ton/h)	58.79	73.57	86.71
NOx reduction (%)	8.7	20	30.7
Unburnt coal (%)	7	5	7
Maximum particle size of biomass (mm)	1.4	1.2	1

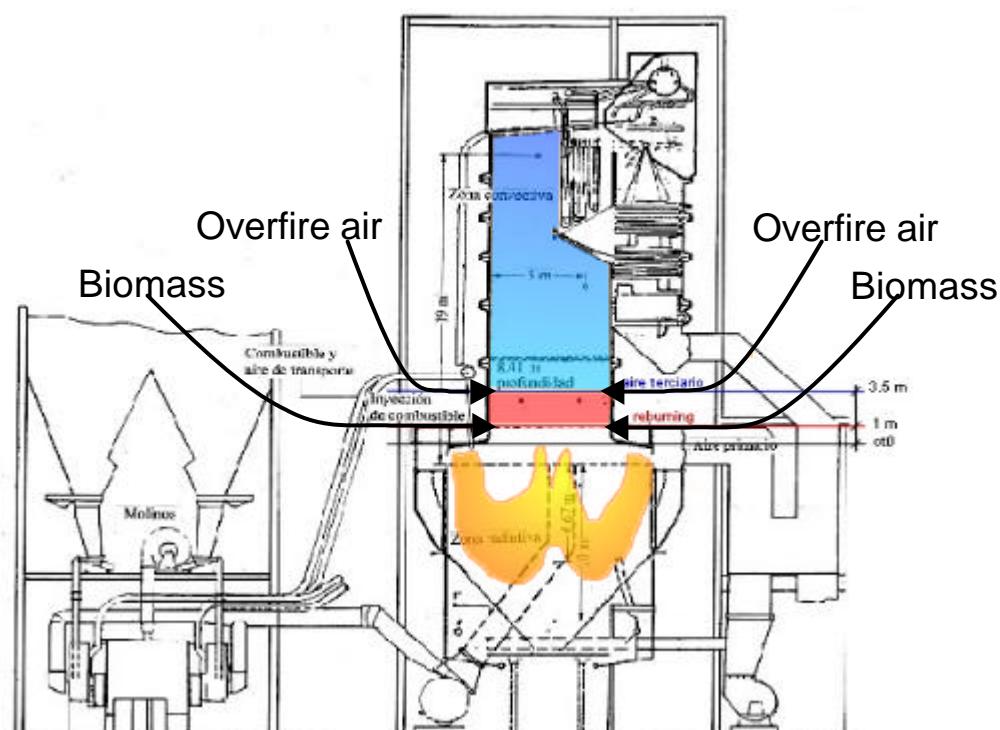


Figure 3 – General view of Narcea-I boiler, indicating the locations of biomass and air ports zones.

4.4 Technological data base set-up

4.4.1 Description of the data base

This data base has been designed in order to allow future enlargements or modifications of it, so it can be used in different projects. That is the reason why no key has been introduced.

It has been considered that the best way to cover the objectives stipulated in the contract was in an interactive way, because of that lot of attention has been paid to the way that information has to be introduced and presented.

The base of this data base is to allow users to find out which are the best technologies available, that satisfy their objectives.

The data base is structured in three (3) main windows, the first one appears automatically once the programme is opened and has been developed to simplify the access to the information.

The other two (2) windows are opened through this first window, which centralise all the work done in the data base.

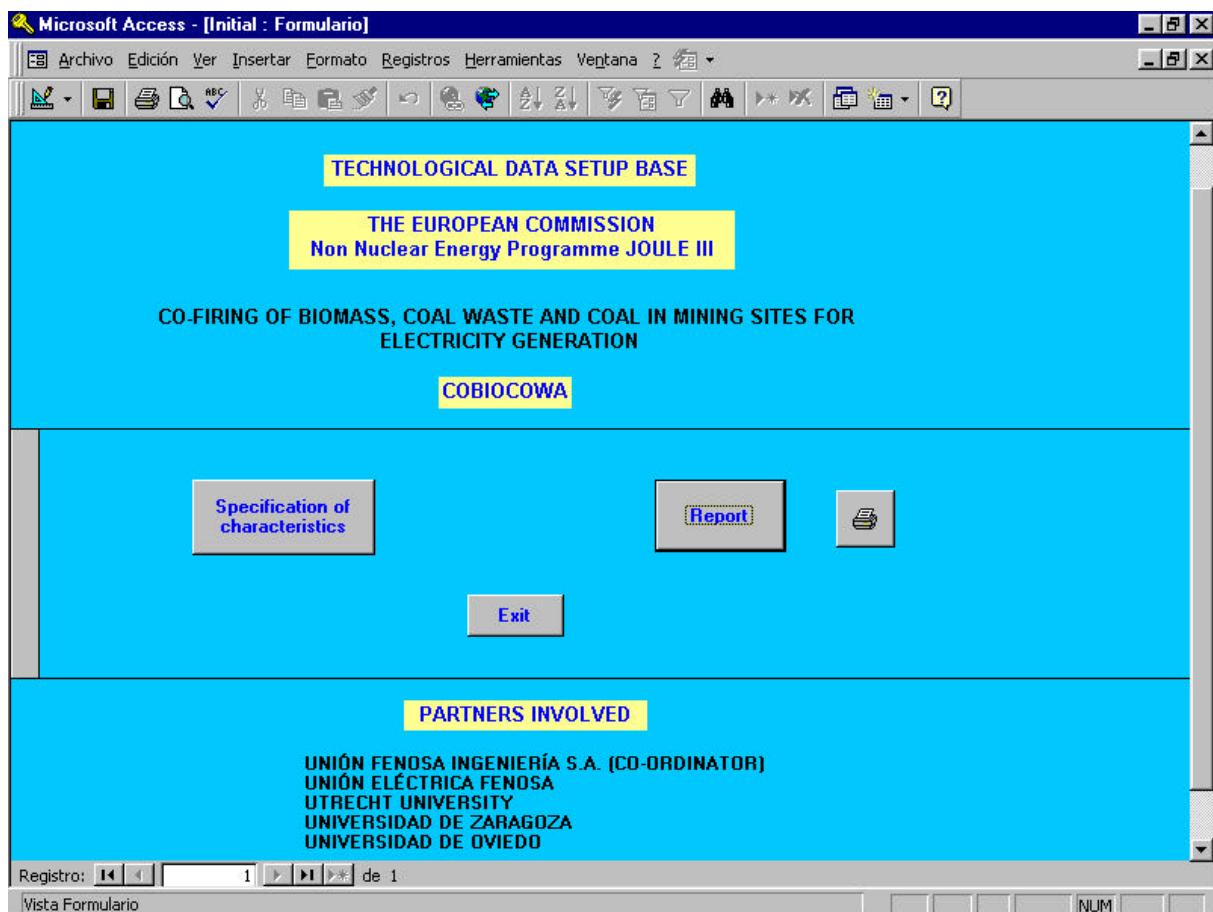


Figure 1: First Window

This first window (Figure 1) as previously said, appears automatically once the programme is opened.

The window contains the identification of the project and participants and four (4) buttons to operate the data base.

Two of the buttons (Specification of characteristics and Report) link with the other two main windows, another button (the printer icon) can be used for printing the report and the last one (Exit), exits the programme so it is better not to use it until the enquiry has finished.

Microsoft Access - [information input]

The screenshot shows a Microsoft Access application window titled "INFORMATION INPUT". The main title bar includes standard menu options like Archivo, Edición, Ver, Insertar, Formato, Registros, Herramientas, Ventana, and Ayuda. Below the menu is a toolbar with various icons. The main area is a form titled "COBIOCOWA". It contains several sections with dropdown menus for selecting values from 2 (very important) down to -2 (indifferent). The sections are:

- Construction related criteria** (highlighted in yellow):
 - Simplicity of technical solution
 - Little space required
- Emission related criteria** (highlighted in yellow):
 - NOx reduction
 - Modest solid waste production
 - Emission related equipment, reduced cost
- Fuel related criteria** (highlighted in yellow):
 - Fuel moisture design flexibility
 - Fuel size design flexibility
 - Fuel moisture switching flexibility
 - Fuel size switching flexibility
- Efficiency related criteria** (highlighted in yellow):
 - Boiler efficiency
 - Carbon burnout efficiency
 - Modest excess air requirement
 - Modest fan capacity

A note at the bottom left says: "Please for every criterion select a value from '2' (very important for the project) to '-2' (indifferent to the project)". A vertical scroll bar is on the right side of the form.

Figure 2: Information input window

This second window (Figure 2) is opened by the link located in the first window.

The top section of the window contains exist and recording buttons. The intermediate section allows to introduce all the information needed for the model, this information is classified as follows:

- 1. Name
- 2. Construction related criteria
 - Simplicity of technical solution
 - Little space required
- 3. Fuel related criteria
 - Fuel moisture design flexibility
 - Fuel size design flexibility
 - Fuel moisture switching flexibility
 - Fuel size switching flexibility
- 4. Emission related criteria
 - NOx reduction
 - Modest solid waste production
 - Emission related equipment, reduced cost
- 5. Efficiency related criteria
 - Boiler efficiency
 - Carbon burnout efficiency

Modest excess air requirement
Modest fan capacity

In the last section an explanation of the possible values (2,1,0,-1,-2) for the different criteria is given, the top value of the scale is "2" meaning very important for the project and the bottom value is "-2" meaning indifferent to the project.

In order to exit this window two (2) options are contemplated, it is possible to use the exit button located in the first section or to use the "X" located in the right corner.

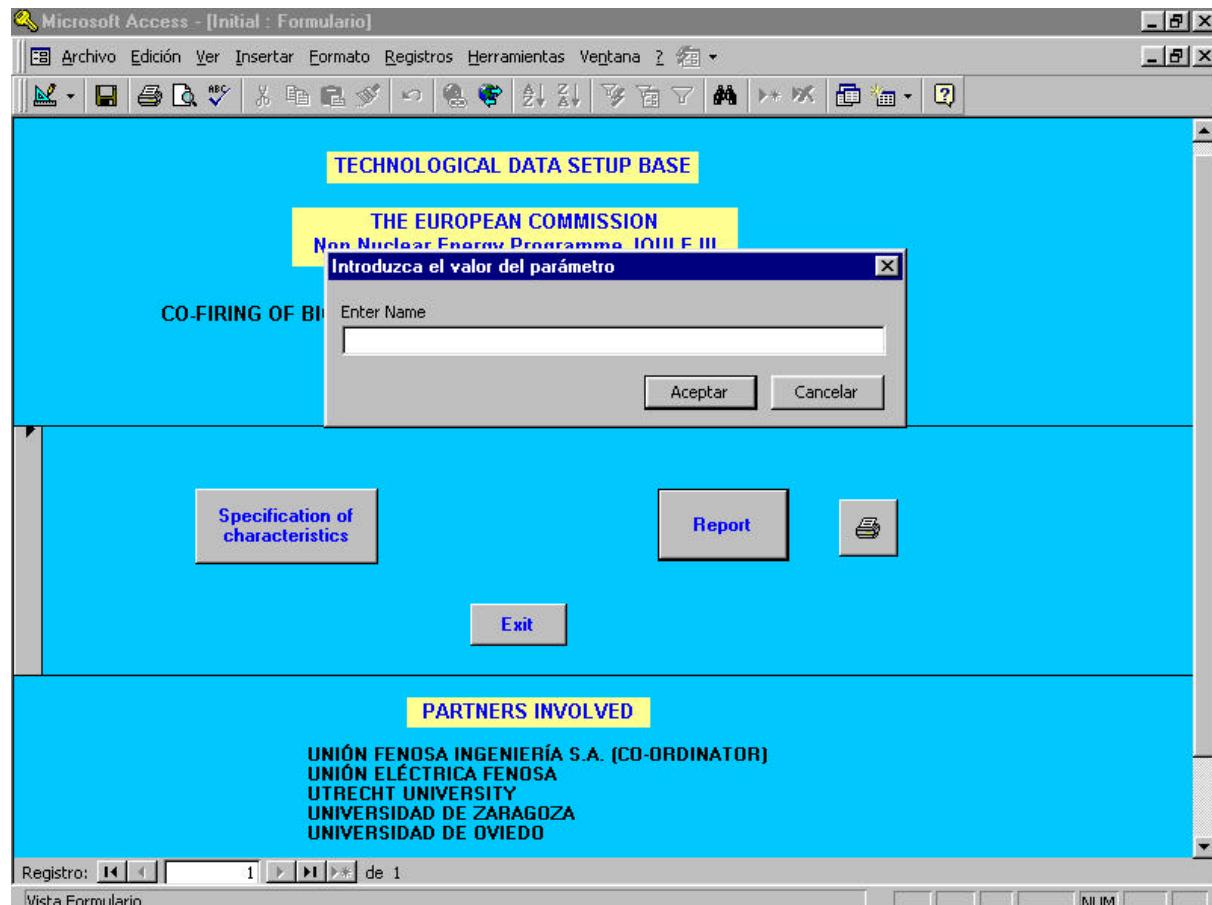


Figure 3: Entering name box

To open the last window, the Report one, it is necessary to use the link located in the first window. It will appear a box asking for entering a name (Figure 3). This has to be exactly the same to the name entered in the Information input window.

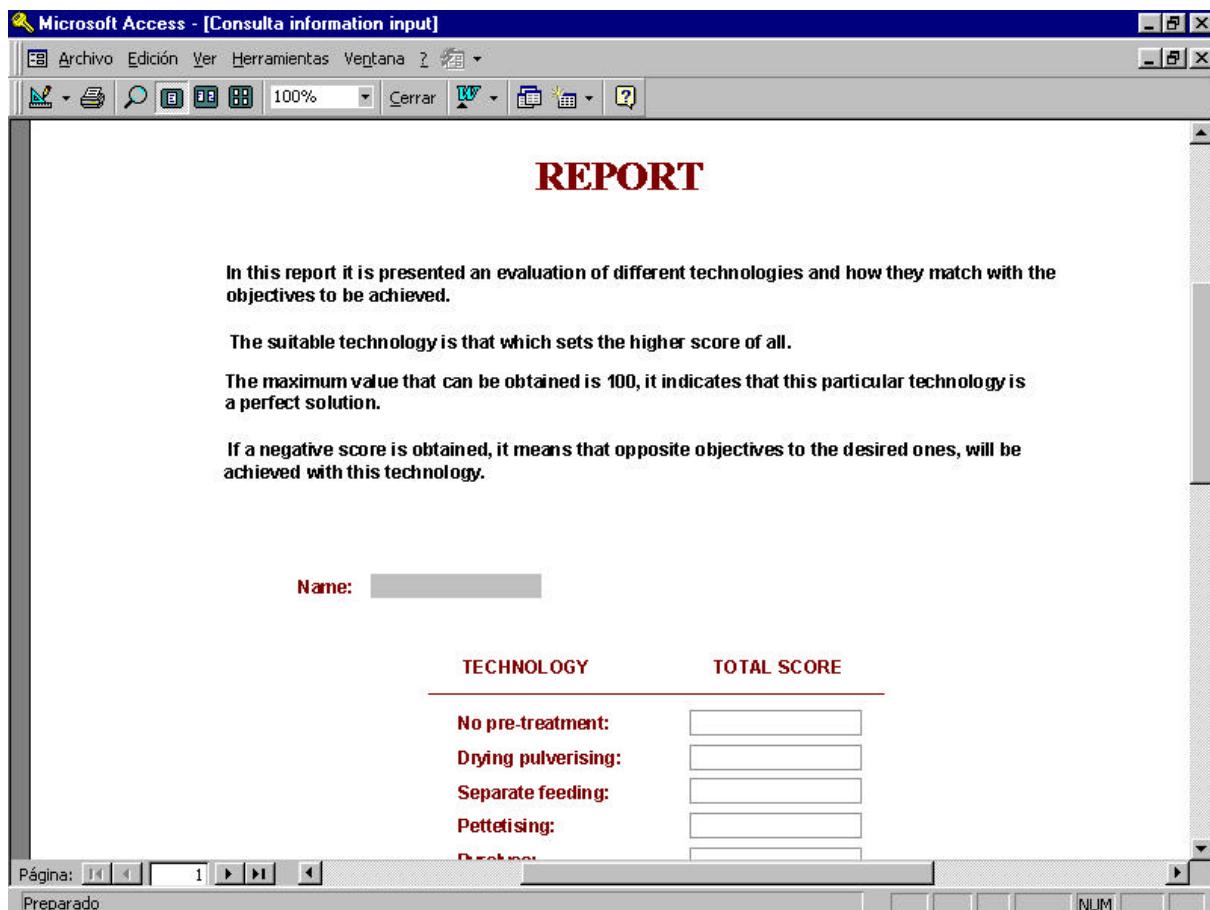


Figure 4: Report window

When the name has been entered, the Report window (Figure 4) emerges with the results of the inquiry.

In order to simplify the analysis of the results some explanatory marks are made at the top of the window:

- 1. In this report it is presented an evaluation of different technologies and how they match with the objectives to be achieved.
- 2. The suitable technology is that which sets the higher score of all.
- 3. The maximum value that can be obtained is 100, it indicates that this particular technology is a perfect solution.
- 4. If a negative score is obtained, it means that opposite objectives to the desired ones, will be achieved with this technology.

The main body of the report consists in an evaluation of the different technologies that are considered in this project:

- 1. No pre-treatment
- 2. Drying pulverising
- 3. Separate feeding
- 4. Pettetising
- 5. Pyrolyse

- 6. CFB gasifier
- 7. Grate
- 8. BFB boiler
- 9. CFB boiler

In order to exit this window, the “X” located in the right corner has to be used.

4.4.2 Conclusions

Significant advances on the state of art of technologies might have influence on the validity of the results of this tool. It so, a new review of the data base programming should be afforded.

4.5 Technical feasibility of cofiring implementation

4.5.1 Analysis of the different options considered

Two main possibilities have been considered:

- 1. Co-firing of coal and biomass blended and injected through the same burner.
- 2. Co-firing of coal and biomass at separate points along the combustion chamber using biomass as a reburning fuel.

Considering the results obtained in the semi-industrial furnace specifically adapted to co-fire coal and biomass that has been used for this study, the best option is the second one basically because it leads to a further reduction of the NO_x.

When the biomass load is around 20% of total thermal input, a NO_x reduction close to 50% is achieved using reburning.

4.5.2 Reburning option

4.5.2.1 Detail modifications to carry out

In this section, it has been considered the technical modifications needed to shift Narcea power plant into a reburning plant.

4.5.2.1.1 Lorry reception area

It has been considered appropriated to have two reception areas, one for coal and one for biomass, which will simplify operation and maintenance. The first reception area is already built but it will be necessary to build the second one for the biomass.

4.5.2.1.2 Biomass transport to the storage area

The lorries will unload the sawdust in a ditch, from the ditch to the storage area the biomass will be transported using pumps.

4.5.2.1.3 Biomass storage area

A new building will have to be built in order to store enough sawdust to keep the plant on going for a week, in case that no supply would be available during that period of time.

It has only been considered seven (7) days because the sawmills are geographically close to the plant and they have their own storage areas.

4.5.2.1.4 Biomass transport to the feeding system

The sawdust transport from the storage area to the hopper will be a pneumatic transport. The pipes that transport the sawdust will be design trying to avoid deposits, it is important to pay attention to the airflow and the angles of the turns.

4.5.2.1.5 Biomass injection

It has been considered to locate eight (8) injection points in order to feed the sawdust to the boiler. These injection points will be at the same height that the coal injection points.

Each injection point will have it's own feeding system consisting in a hopper and a worm gear.

4.5.2.1.6 Overfire air injection

The overfire air injection points, eight (8), will be located 3.5 meters above the biomass injection points.

4.5.2.1.7 Gas treatment equipment

As described in the work carried out by Zaragoza the use of biomass as a reburning fuel leads to a slight decrease of the overall particles generated in the combustion. However the size of these particles also decreases, difficulting the removal process. Thus the removal efficiency should be decreased and therefore some modifications in the gas treatment system have to be performed.

It has been considered as the best option the replacement of the current mechanical separator by two multicyclones. The actual electrostatic separator downstream will not be modify.

By implementing this modification it will be possible to collect the new particles generated in the boiler.

4.5.2.2 Restrictions to take into account

This study has been developed considering that the biomass used in cofiring is sawdust. It has also been assumed that no size reduction or drying is needed.

These hypotheses are based in the analysis made to the samples taken in the studied area and the analysis of the conditions required by the boiler. If this study is going to be extrapolated to a different country or to a different boiler, the meteorological and environmental conditions as well as the restrictions of the boiler itself, should be studied because they can change the required pretreatment.

4.5.2.3 Operational problems to overcome

The main problems that will have to be faced during the usual operational activities are the ones related to the use of small size particulates (sawdust). The sawdust can form deposits, blocks, and depending on the humidity can even be compacted.

The operational problems can be minimised by doing a good design of the overall modifications and carrying out good operation practises. It is important to respect the recommended airflows, temperatures, humidity of the sawdust, etc

4.5.2.4 Environmental impact

4.5.2.4.1 Atmospheric impact

With the proposed modifications several environmental benefits, based on the semi-industrial tests, will be obtained:

- 1. Reduction of NO_x close to 50 %
- 2. Reduction of SO₂

On the other hand some side effects related with the environment like a slight increase of CO and the subsequent impact in the greenhouse effect might occur.

4.5.2.4.2 Liquid and solid wastes

The solid wastes that would be generated, taking into account the proposed modifications and the solid wastes generated by the actual Narcea power plant can both be classified in the same group for treatment according to the Spanish legislation. Therefore the actual treatment will not be modified.

The composition of the liquid wastes will not be significantly influenced by the modifications proposed, therefore no changes in this area have been considered.

4.5.3 Conclusions

In order to determine the technical feasibility of co-firing biomass with coal at Narcea I power plant, located in Tineo (Asturias-Spain), it has been contacted the boiler supplier (Foster Wheeler).

After several meetings it has been conclude that the proposed modifications are technically feasible. Event though it is necessary to evaluate the economic feasibility that will be basic in the determination of the overall feasibility of the project.

4.6 Economic assessment

4.6.1 Estimated investment costs

This section includes the capital necessary to carry out the proposed modifications.

In the assessment it has been assumed that the actual Narcea's capital allowance is zero. For extrapolating this study to other European countries with similar power plants it is necessary to check this condition.

INVESTMENT COSTS (Euros)	
Land required	6454.870
Civil works	5437.957
Biomass storage area	129554.169
Biomass transport equipment	7632.854
Feeding equipment	330556.657
Gas treatment equipment	166748.404
Instrumentation & control	63449.208
Installation costs	253796.834
Engineering project	192726.191
Building contractor	809450.001
Unforeseen expenses	231271.429
TOTAL	2197078.573

Table I: Investment costs (Euros)

4.6.1.1 Land required

It has been estimated the land required to install the equipment and buildings needed to carry out the proposed modifications. It has also been taken into account the average selling price of the area.

4.6.1.2 Civil works

It includes mainly the lorry reception area, the ditch where the lorries unload the biomass and the foundations of the biomass storage area.

4.6.1.3 Biomass storage area

It has been considered a building with enough capacity to store the required sawdust to keep the plant on going for a week, in case that no supply would be available during that period of time.

It has only been taken into account seven (7) days because the sawmills are geographically close to the plant and they have their own storage areas.

4.6.1.4 Biomass transport equipment

It includes the transport of the sawdust from the ditch to the storage area and the pneumatic transport of the sawdust from the storage area to the hopper.

4.6.1.5 Feeding equipment

It has been calculated taking into account the eight (8) injection points required to feed the sawdust to the boiler and the eight (8) injection points required for the overfire air.

Each sawdust injection point has its own feeding system consisting in a hopper and a worm gear.

4.6.1.6 Gas treatment equipment

It includes the two multicyclones required to adapt to old particle removal system, consisting in a mechanical collector and an electrostatic precipitator, to the new needs.

4.6.1.7 Instrumentation & control

In every plant it is fundamental to be able to measure characteristic parameters such as temperature, pressure, etc and to be able to work under control. In this section it has been considered the money required to adapt the actual instrumentation and control system to the new necessities created by the modifications.

4.6.1.8 Installation costs

It includes the money needed to locate and connect the equipment correctly.

4.6.1.9 Engineering project

In order to fulfil the modifications of the plant, it will be necessary to carry out an engineering project, which includes technical, environmental and economical studies.

4.6.1.10 Building contractor

Once the engineering project has been elaborated, the works may begin. It is necessary to select an engineering company who will carry out the mentioned works, it can be either the same who elaborated the project or a different one.

4.6.1.11 Unforeseen expenses

Although it is quite difficult to calculate, it has been considered the standard amount of money normally assigned to this section in this kind of project. It includes all that money required to solve unexpected problems.

4.6.2 Operational and maintenance costs

This section includes the capital necessary to operate and maintain the plant once the modifications have been carried out.

OPERATIONAL& MAINTENANCE COSTS (Euros/year)	
Total input costs	1199019.148
Transporting cost	34257.689
Maintenance and reparation cost	2532184.198
Total labour	6088553.123
Private security	159869.212
Management	5192.744
Insurance	500000.000
Environmental cost	477654.370
Rent of equipment	17429.350
Various	1901920.845
TOTAL	12916080.679

Table II: Operational and maintenance costs

4.6.2.1 Total input costs

It has been calculated according to the data collected from the Tineo area in Spain and the data provided by Union Fenosa, the company who manage the Narcea I, power plant. It has been considered not only the coal and sawdust but also other consumptions such as oil.

4.6.2.2 Transporting cost

This cost has been estimated considering the distance travelled, the quantity to be transported and the transporting price of the different products.

4.6.2.3 Maintenance and reparation cost

It includes the money required to carry out the usual maintenance activities and the reparation of the broken devices, considering the fact that Narcea I, is an old power plant and therefore the costs are bigger than usual.

4.6.2.4 Total labour

It has been calculated taking into account the number of workers required in the plant once the modifications have been completed, their qualification and therefore their salary.

4.6.2.5 Private security

This cost has been estimated considering the standard prices asked by the private security companies in order to guarantee the security and vigilance of the whole plant

4.6.2.6 Management

It has been considered that the proposed modifications will not change the Narcea I management cost, therefore an equal data has been used.

4.6.2.7 Insurance

It has been selected the same type of insurance that has been contracted in the actual Narcea I, power plant.

4.6.2.8 Environmental cost

It includes the money invest in the treatment of the used oil, the environmental consultancies that will be carried out, etc.

4.6.2.9 Rent of equipment

It has been considered the same rented equipment that the actual Narcea I, power plant is using, therefore the proposed modifications do not affect this category.

4.6.2.10 Various

This cost includes many different costs of minor amount, which are considered all together here.

4.6.3 Incomes

4.6.3.1 Electricity production

It has been calculated considering the Spanish unitary selling price of electricity and the output electricity.

	Unitary selling price (Euros / kWhe)	Generated power (kWe)	Consumption in plant (kWe)	Plant output (kWe)	Hours/year of operation	Annual incomes (Euros/year)
Electricity production	0.036	60000.0	4400.0	55600.0	6450	12946182

Table III: Electricity production

4.6.4 Analysis of the cash-flow

In order to determine the feasibility of the proposed modifications, the study sets the Net Present Value (N.P.V.) and the Internal Rate of Return (I.R.R.) as suitable evaluation techniques.

Both techniques are connected. By definition, the Internal Rate of Return (I.R.R.) is the rate of discount that reduces the Net Present Value (N.P.V.) of a project to zero.

Both of them have been calculated considering a rate of discount of 10%.

3.6.5.1 Results

General Inflation	3%					
Taxes	32.5%					
	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Investment Costs (Euros/year)						
Investment	219707 8.573					
Own funds	100% 219707 8.573					
Long-term debt	0%					
Costs (Euros/year)						
Capital allowance	439415.7 15	439415. 715	439415. 715	439415.7 15	439415.7 15	
Operational costs	1291608 0.679	1330356 3.099	137026 69.992	1411375 0.092	14537162 .595	
Incomes (Euros/year)						
Total incomes	1294618 2.000	1333456 7.460	137346 04.484	1414664 2.618	14571041 .897	
Cash flow (Euros/year)						
Pre-tax profit	-409314 .394	-408411 .354	-40748 1.223	-406523 .188	-405536 .413	
Taxes	-133027 .178	-132733 .690	-13243 1.398	-132120 .036	-131799 .334	
Cash flow	-2197078.573 99	163128.4 051	163738. 889	164365. 62	165012.5 36	
N.P.V. 10%						-157438951%
I.R.R.						-25.8%

Table IV: Cash-flow, N.P.V. and I.R.R.

The calculation of the cash-flow, the Net Present Value (N.P.V.) and the Rate of Return (I.R.R.) is summarised in Table IV.

In order to carry out a easily extrapolating study some hypothesis have been considered:

- 1. 100% of the investment has been done by own financing.
- 2. Narcea Power Plant will go on for another five years.
- 3. Actual Narcea's capital allowance is zero.
- 4. No investment grant will be received.

As can be inferred by the analysis of the obtained data, the proposed modifications are not economically feasible. Both techniques the Net Present Value (N.P.V.) and the Rate of Return (I.R.R.) indicates so as N.P.V. is lower than zero (0) and I.R.R. is lower than ten

(10).

4.6.5 Conclusions

The implementation of the proposed modifications in Narcea power plant would have a positive influence in the environmental impact of the plant, mainly in the reduction of NO_x emissions. It would also have a positive influence in the local economy because it would help to develop a biomass market, which has associated the generation of employment

Because of the above mentioned reasons it has been studied the economical feasibility of the project. To determine this feasibility it has been considered not only the modifications (because the avoided costs will not possibly compensate the investment required) but the overall economical situation of the plant.

After performing the economic analysis of the feasibility of the modifications, it has been concluded that the modifications are not economically feasible because the incomes associated to the electricity selling can not compensate the investment required and the operational and maintenance costs. Additional benefits in relation to NO_x reduction are not valuable, due to the fact that no regulation applies to set incomes/cost reduction about this environmental effect.

If the regulation applicable, the remaining life of the plant and the market conditions are modified, the economic feasibility of the proposed modifications will be affected. The modifications could become economically feasible.

5. Results and conclusions

5.1 Results

5.1.1 Availability of biomass and high ash coals in the Narcea Power Plant area

Wood residues produced by twenty-one sawmills in the vicinity of the Narcea Power Station were assessed. Four main types of wood are processed: eucalyptus, pine, oak and chestnut tree. Actual prices were obtained when possible. The net heating value is strongly influenced by the moisture content of the wood that is very variable depending on the industry, quality of wood and storage conditions. Annual production of sawdust and low quality wood from these industries was estimated to be about 28,000 t/year.

As for the high ash coals the possibility checked was the obtention of raw coal from the mines of the area. Five mining facilities were contacted and now only four of them remain active. If the production remains similar is possible to get several hundred thousand tons per year.

This result belongs to Universidad de Oviedo.

5.1.2 Procedures for the Determination of Heating Values of High Ash Content Coals

The determination of the heating values for the coals studied were carried out without noticeable problems. Other coal samples tested in our laboratory indicated that if the ash content is big enough, the determination of the heating values presents some difficulties. If the ash content exceeds 55% the calorimetric techniques should be carried out by using modified procedures.

This result belongs to Universidad de Oviedo.

5.1.3 Report Biomass pre-treatment and co-firing technologies

A review is given of the state-of-the-art in co-firing coal, biomass and coal waste. Various previous co-firing projects and studies within Europe are assessed. Analysed are: the drying, sizing, screening and store of biomass as well as final mix with mine waste and/or coal. For energy generation the behaviour and consequences of combustion are studied, including efficiency and ranges of share of fuels mixtures. Waste production is studied, characterisation of ashes and emissions including heavy metals and levels of NOx, SO2 and particles.

This result belongs to Utrecht University

5.1.4 Report: Modelling of the Narcea power plant for evaluating the impacts of various co-combustion schemes on plant performance and emissions

The report describes the development of the Aspen plus computer model (5.1.5), its results on simulations of co-firing scenarios, and consequences for the COBIOCOWA project. Relations between feedstock types and combustion behaviour and emissions are given and translated to the model. Effects of different co-firing schemes on plant efficiency and emissions are presented and discussed. The report serves as an important input to economical analysis.

This result belongs to Utrecht University

5.1.5 Aspen Plus Computer model for cofiring in pulverised fuel boiler

The Narcea I unit is modelled in Aspen Plus. Numerous combinations of feed streams (coal, coal waste, wood residues and sawdust) can be analysed for their influence on pretreatment energy use, boiler potential, boiler and plant efficiency, and emissions. Base case simulation shows that the model is consistent with existing plant. Cofiring 5 % sawdust by heating value gives a modest decrease in net plant efficiency from 33.4 % (HHV) to 33.2 %, cofiring 50 % residues leads to a dramatic power loss of biomass cofired. The model and specific scenario results are reported in result 3. The model can easily be tailored to other pulverised fuel boilers as well.

This result belongs to Utrecht University

5.1.6 Database on biomass combustion

The lab-scale tests performed in the project have resulted in a thorough knowledge of the combustion behaviour of a range of wood residues.

Very little information on this subject, and with the characteristic of being valid for the design of combustion equipment, is available. In this work, the experiments have been carefully designed to reproduce the combustion conditions inside practical power-generating boilers. As a result, this database is considered a valuable tool for the evaluation or design of new biomass-fired combustion equipment or for the retrofitting of existing plants to implement a cofiring strategy.

This result belongs to Universidad de Zaragoza.

5.1.7 Database on biomass/coal cofiring

Detailed characterisation and parametric analysis of the performance of two different cofiring strategies:

- Combustion of pulverised coal/biomass blends in a multifuel burner.
- Injection of biomass through specific ports in a reburning configuration

This result belongs to Universidad de Zaragoza.

5.1.8 Technological data-base

This data-base has been designed in order to allow users, in an interactive way, to find out which are the best technologies available, that satisfy their objectives in the field of combustion.

The programme can be modified without restrictions as no key has been entered which simplify future reviews or future extrapolations to different projects.

This result belongs to Unión Fenosa Ingeniería.

5.1.9 Analysis of technological modifications

This work analyses in detail the modifications required to co-fire biomass with coal in an industrial plant equivalent to Narcea I.

Narcea I, is a 65 MWe coal fuelled plant located in Tineo (Spain).

The scope of the recommendations goes from the pretreatment to emissions, liquids and solid wastes.

This result belongs to Unión Fenosa Ingeniería.

5.2 Conclusions

The present project has covered the different aspects required to implement the best technology in Narcea I, which allow to increase the share of renewables in the energy system, to reduce fossil fuel use and to reduce environmental impact while at the same time using local resources.

According to the assessment carried out, the use of coal residues is not possible from an economic point of view, and is also environmentally unacceptable. Due to this circumstance, it has been studied other coal-based products such as high-ash coals or coal from the mine without any kind of pretreatment, and possibly with less additional costs.

The analysis of biomass and coal that has been performed, indicates that low heating values of wet biomass samples collected in the Tineo area range in the interval 8 kJ/g to 10.5 kJ/g depending mostly of the water content of the samples. Whereas low heating values of coals collected from mining industries in the region range in the interval 14 kJ/g to 22 kJ/g depending of the moisture and ash content (LHV decrease as ash concentration increase):

In the lab scale tests two important conclusions were obtained. The first one is connected with the use of high-ash coal in a real boiler and the second one is connected with the selection of the most adequate biomass fuel.

The high-ash coal and the standard coal have similar kinetic parameters, therefore the high-ash coal do not offer any possible advantage to the overall process because it does not improve the kinetic aspect and it worsens the thermodynamic and environmental aspects (lower LHV and higher ash production than standard coal).

The Oak wood provides better kinetic values than other types of wood (Chestnut and Eucalyptus) that have been analysed, therefore the Oak sawdust has been found as the best biomass fuel.

After carrying out the modelling and testing stage several conditions have been specified as the most adequate for implementing co-firing of biomass with coal in Narcea I:

- The reburning technique is the most promising for Narcea I
- The amount biomass is equivalent to 20% of total thermal input
- The excess oxygen in the flue gases is set at 5% by vol.
- The unburnt fraction of the biomass is similar to the nominal value in the current coal-fired plant (around 5%).

The use of biomass as a reburning fuel provides good environmental results, the NO_x emissions decrease. NO_x reduction rates exceeding 50% have been measured in the most favourable case (lowest excess oxygen from the primary flame and highest amount of biomass). In the selected case for Narcea, the reduction is around 20%.

The main modifications required to implement the co-firing of biomass and coal are: a lorry reception area, a biomass transport to the storage area, a biomass storage area, a biomass transport to the feeding system, eight biomass injection points, eight overfire air injection points and two multicyclones.

After performing the economic analysis of the feasibility of the modifications, it has been concluded that the modifications are not economically feasible because the incomes associated to the electricity selling can not compensate the investment required and the operational and maintenance costs. Additional benefits in relation to NO_x reduction are not valuable, due to the fact that no regulation applies to set incomes/cost reduction about this environmental effect.

If the regulation applicable, the remaining life of the plant and the market conditions are modified, the economic feasibility of the proposed modifications will be affected. The modifications could become economically feasible.

6 Exploitation plans and anticipated benefits

All the results have been classified by the partners as “exploitable results of interest for third parties”.

Therefore the partners consider the results of the commercial interest, but do not intend to exploit the results themselves, or at least not exclusively or do not have sufficient resources within the consortium. It is in the interest of the partners to make information on such results available for dissemination and further exploitation.

It is considered by the partners that the COBIOCAWA project will have a high economic influence among future projects for the implementation of co-firing of biomass and coal in a coal fuelled plant. The results that have been obtained identify the key points (scientific, technical and economical) for a successful implementation.

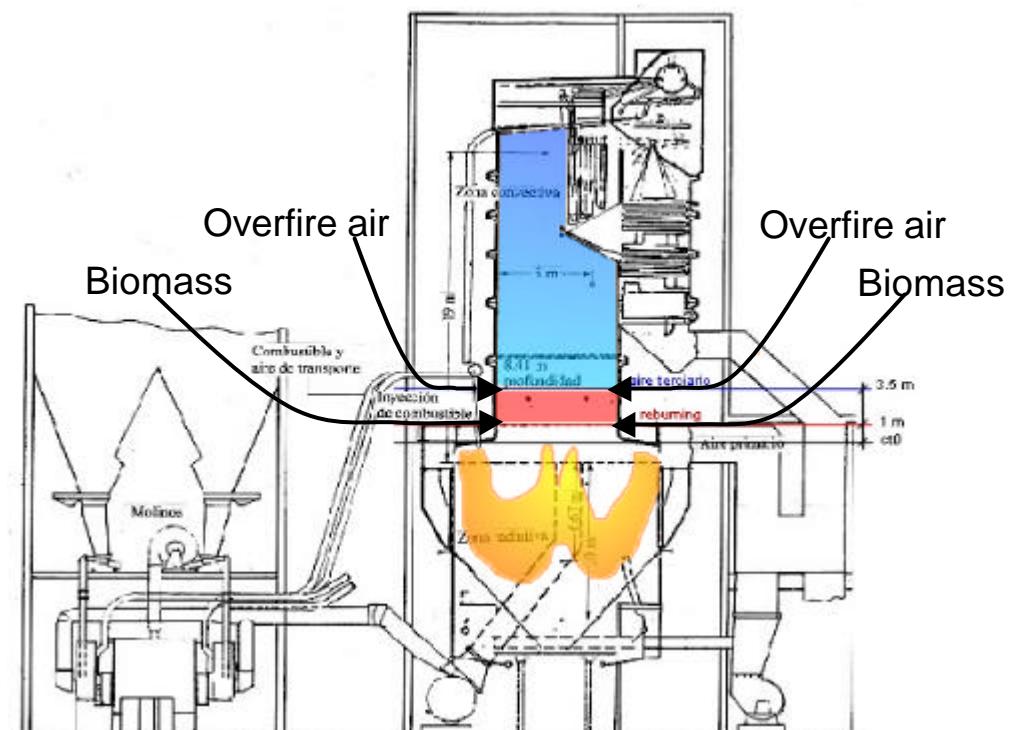
7 Photograph, diagram or figure to illustrate potential applications of the project

The potential application of this project is to implement the proposed modifications in a real boiler.

It has been studied the economical feasibility of the project in Narcea power plant. To determine this feasibility it has been considered not only the modifications (because the avoided costs will not possibly compensate the investment required) but the overall economical situation of the plant.

After performing the economic analysis of the feasibility of the modifications, it has been concluded that the modifications are not economically feasible because the incomes associated to the electricity selling can not compensate the investment required and the operational and maintenance costs. Additional benefits in relation to NO_x reduction are not valuable, due to the fact that no regulation applies to set incomes/cost reduction about this environmental effect.

If the regulation applicable, the remaining life of the plant and the market conditions are modified, the economic feasibility of the proposed modifications will be affected. The modifications could become economically feasible and therefore the direct application of this project will be to implement the mentioned modifications in a real boiler.



Photograph –1

General view of Narcea-I boiler, indicating the locations of

biomass and air ports.