FINAL TECHNICAL REPORT
FINAL PUBLISHABLE REPORT

CONTRACT N^{O}: ERK5 – CT – 1999 – 0004

PROJECT N^{O}: 1999/C77/13 AND 1999/C77/15

ACRONYM: STRAWGAS

TITLE: STRAW GASIFICATION FOR CO-COMBUSTION IN LARGE CHP-PLANTS

PROJECT CO-ORDINATOR: ENERGI E2 (FORMER ELKRAFT POWER COMPANY)

PARTNERS: FOSTER WHEELER ENERGIA OY AND ENERGI E2 A/S

REPORTING PERIOD: FROM 1. JANUARY 2001 TO:31. MAY 2001

PROJECT START DATE: 1. APRIL 2000 DURATION:14 MONTH

DATE OF ISSUE OF THIS REPORT: 31. MAY 2001

Project funded by the European Community under the '.....' Programme (1998-2002)

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0. PREFACE

This is the final report of the STRAWGAS-project “Straw gasification for co-combustion in large CHP-plants”. The report covers process validation of the gasification and gas cleaning tests that were carried out in 2000 and the design study of a 100 MW_{th} gasifier. Process validation and design study covers gasification of 100% straw and a fuel mix of straw and wood.

The project partners Foster Wheeler Energia Oy and ENERGI E2 A/S (former Elkraft Power Company) have executed the major part of the project with VTT Energy (Finland) and TK energi (Denmark) as valuable sub-suppliers. The project has received substantial economical support from the European Commission.

The experimental research consisted of 3 main tasks:

- The capability of the developed feeding system to feed loose straw into the gasifier
- The optimal process conditions and additives for gasifying loose straw
- The capability of the selected gas cleaning system to make the gas suitable for co-combustion in large CHP-plants

In the design study a full-scale straw gasification plant of 100 MW_{th} and the integration with an existing large CHP plant was investigated. The practical solutions of all unit operations were developed. The budget for a complete plant was calculated and consequently the overall project economy was assessed. The result of the process validation and design study can be the technical and economical basis for a decision to built a demonstration plant.

This project was carried out in the period from April 2000 to May 2001.

1. SUMMARY

Straw-gasification for Co-combustion in large CHP-plants
Foster Wheeler Energia Oy and ENERGI E2 A/S have carried out a test programme regarding straw gasification in a 3 MW_{th} atmospheric CFB gasifier with gas cleaning. In parallel with this programme, a design study has been conducted with a view to create a decision basis for erecting a 100 MW_{th} demonstration plant.

This R&D work has received subsidies from the EU under the project name STRAWGAS.

Overview of the testing
Four test series have been conducted:
- Running in of test pilot plant with straw pellets
- Tests with loosely cut straw and a specially designed cutter
- Tests with loosely cut straw. Long-term testing with gas cleaning etc.
- Burning of filter ashes in a low-temperature CFB

Detailed test reports have been prepared for all test periods that have included gasification of more than 450 Hesston bales (500 kg) of Danish straw.

Gasification process
The conclusion of the tests is, that the actual gasification process can be carried out without problems, i.e. without sintering of the bed material, and also that the temperature can be controlled by feeding with straw and adding air and steam. A gasification efficiency ratio of approximately 95% conversion of the carbon has been attained.

Sand and limestone have been used as bed material.

Gas cleaning
The actual gas cleaning procedure with gas cooling followed by filtering in a warm fabric filter has worked satisfactorily during the relatively short tests. It is crucial to avoid hot spots in the filter, since this prevents glowing and subsequent destruction of filter.

Straw feeding
The straw feeder and cutter have worked satisfactorily in a small scale. Since less than optimal steel qualities were chosen, wear and tear has been detected on the parts experiencing the heaviest load.

A demo plant with an input capacity of 100 MW_{th} requires a feeding system that is up-scaled by a factor of 10.

Filter ash
The 25-30% carbon content in the filter ash is relatively high. Because of the high carbon content, Foster Wheeler has conducted tests, at its own expense, burning filter ash in a CFB at relatively low temperatures. It was possible to reduce the carbon content in the filter ash to less than 4%. The content of PAH was less than 1 mg/kg, while the pH-value was 12, which is a high value.

Description of design study results
Concurrently with the testing, a comprehensive design study has been conducted with a view to creating a design basis for a 100 MW_{th} demonstration plant. The design study includes the following technical aspects:
- Main process description, including a flowchart.
- Process safety measures.

- Description of the gasifier. The gasifier will largely resemble the RDF/wood gasifier in Lahti, Finland of approximately 70 MW_{th}.
- Gas cooler and gas cleaning system.
- Description of connection system to the existing boiler and relevant burner design.
- Wood-chip and straw feeding system.
- Wood-chip and straw storage facilities.
- Nitrogen system.
- Ash processing and handling system.
- Electric systems.
- C&I systems.
- Buildings
- Operating philosophy

A plant design already exists where most of the above items have been tested and satisfactory solutions have been found.

Economy
Capital budget for a 103 MW_{th} complete straw gasifier coupled to a boiler is EUR 38.4 mio. all incl. For a 103 MW_{th} 50/50% straw and wood chip gasifier the equivalent budget is EUR 42.3 mio. The higher price in the case of straw and wood is due to additional expenses for the handling and storage of wood chips.

Calculations covering a period of 20 years shows that the generated NPV for 100% straw is minus EUR 1.4 mio and for 50/50% straw and wood EUR 7.0 mio. These calculations are only valid for Danish conditions.

Overall assessment
The actual gasification process with gas cleaning already proved technically feasible during testing.

Technical development or a greater knowledge base will be needed for the following components and processes:
- Fuel feeding
- Gas cooling
- Gas filtering
- Ash processing

2. BACKGROUND

2.1 Introduction

ENERGI E2 and Foster Wheeler Energia Oy agreed in 1998 to start a joint project aiming at development of an atmospheric circulating fluid bed gasification technology for straw. The project was initiated by the results from a preceding development and test of straw gasification by VTT, which was partly sponsored by the partners. The gas was intended as supplementary fuel in a modern coal-fired power plant, which also supplies district heat (CHP). The project included development and test of a straw feeding system, of gas cleaning equipment and of procedures to ensure reuse of the residues. The project is preparation for a demonstration gasfier with a thermal input of 100 MW_{th}. The use of straw is approx. 150.000 tonnes per year. The energy efficiency from straw to electricity will be almost 40%. The project can lead to demonstration of an efficient and clean method to use straw for power production in a large scale. The method is clean, since straw-gas is burnt in a boiler with modern flue-gas cleaning equipment. Since straw is a major biomass resource in large parts of Europe, this project can help to increase the share of renewable energy in the energy system, and also improve economy and employment in the agricultural sector.

2.2 Introductions of FWE and ENERGI E2

Foster Wheeler Energia Oy
Foster Wheeler Energia Oy (FWEOY) is a Finnish based operating company of Foster Wheeler Corporation. Foster Wheeler Energia Oy's products are Power plants, steam generators, gasifiers and auxiliary equipment to the utility and industrial markets. The company is famous for its energy production systems, based on the circulation fluidised bed technology (CFB). Services also include engineering, manufacturing, erection services, power plant repairs and modernisation.

Foster Wheeler Energia Oy is the leading Fluidised bed technology supplier in the world with long experience in biomass combustion and gasification. Since 1977, Foster Wheeler has supplied more than 180 CFB units up to 235 MW_{el}, having the multi-fuel capability including also biomass and other low-grade fuels. The strategic target of the company is to scale up the CFB boiler up to the utility size. Foster Wheeler Energia Oy has also supplied globally more than 70 bubbling fluidised bed (BFB) boilers, up to 155 MW_{th}, which are mainly biomass fired.

As the leading CFB gasifier supplier, Foster Wheeler has also supplied four CFB gasifiers, gasifying wood and bark. A new concept of a CFB gasifier connected to a pulverised coal-fired boiler is being demonstrated in Lahti, Finland. The CFB gasifier is gasifying wood, bark and miscellaneous industrial and municipal waste. The gas is co-fired with coal in the boiler. A pressurised CFB gasifier based IGCC plant, using woods as the fuel, is being demonstrated at Värnamo, Sweden.

At Foster Wheeler Energia Oy, the Karhula R&D Centre (KRD) in Finland has specialised in the development of atmospheric and pressurised fluidised bed combustion and gasification during its thirty years of history.

ENERGI E2
ENERGI E2 is the second largest energy producer in Denmark. ENERGI E2 owns and operates 7 central power stations and 10 local CHP plants in eastern Denmark and has a share in seven hydropower plants in Sweden. The total production capacity amounts to 4100 MW electricity and 2.900 MJ/s heat.

Besides producing energy, ENERGI E2 is trading electricity on the international power exchanges and sells energy to large costumes. ENERGI E2's customers are primarily electricity trading companies, heating companies and electricity companies with public service obligations. ENERGI E2's market covers Denmark, Norway and the countries surrounding the Baltic Sea.

ENERGI E2 is the market leader in the field of straw-based power production. In 1989, ENERGI E2 commissioned the worlds first straw fired CHP plant, and today ENERGI E2 are operating four highly efficient straw and wood chip-fired facilities. ENERGI E2's next biomass plant will be put into operation in late 2001. It will be the world's largest and most advanced straw CHP plant ever.

In addition ENERGI E2 have been involved in a large number of R&D projects concerning straw utilisation via combustion, gasification and pyrolysis for power generation.

3. WORK PROGRAM

3.1 Introduction

The project is planned as a combination of research, development and demonstration, and therefore the project is divided into two phases with a number of work packages (WP) and subtasks. WP 1 and WP 2 cover the R&D phase. WP 3 to WP 7 covers the demonstration phase. WP 8 covers management and dissemination work. This report covers work packages WP 1, WP 2 and WP 8 only.

The structure of the working plan is:

R&D phase: Process validation and design study.

WP 1: Process validation (see 3.2)
- Task 1.1 Research, development and optimising of fuel feeding systems
- Task 1.2 Gas cleaning system
- Task 1.3 Gasification test with loose straw ($3MW_{th}$)

WP 2: Design study ($100\ MW_{th}$) (see 3.3)
- Task 2.1 Gasifier incl. fuel handling, ash handling, gas cooler and gas cleaner
- Task 2.2 Electrical systems
- Task 2.3 C&I system
- Task 2.4 Buildings

Demonstration phase: Engineering and construction, manufacturing, installation, commissioning and monitoring

WP 3: Engineering, construction and authority approval
- Task 3.1 Straw fuel feeding system
- Task 3.2 Fuel storage
- Task 3.3 Ash handling and storage
- Task 3.4 Gasifier
- Task 3.5 Gas cooler, gas cleaning and connections to boiler
- Task 3.6 Electrical systems
- Task 3.7 C & I system
- Task 3.8 Buildings

WP 4: Manufacturing
- Task 4.1 Gasifier incl. fuel, ash handling and gas cooler
- Task 4.2 Electrical
- Task 4.3 C & I
- Task 4.4 Buildings

WP 5: Assembly/installation

WP 6: Commissioning

WP 7: Monitoring

WP 8: Management and dissemination

Methodology used to achieve the objectives
The major part of the R&D phase was R&D work in pilot scale (WP 1), using an existing 3 MW_{th} gasifier owned and operated by FWEOY. At this pilot scale test facility the straw feeding system and the gas cooling and cleaning system, was developed, tested and optimised. An important part of these tests was a detailed monitoring program.

The results from the tests have given information to the design study in WP 2.

3.2 WP 1: Process validation

Task 1.1: Development and optimising of the feeding system
Loose straw has been used as a fuel in a 3 MW_{th} atmospheric CFB gasifier (ACFBG) pilot plant. Due to the specific properties of straw, a similar feeding system will be constructed for the large 100 MW_{th} gasifier. In the tests, the feeding system has fed loose straw against a slight overpressure in the reactor of the ACFBG pilot plant. The feeding stability and safety was a main concern, under the tests. The feeding system has been modified and improved during the tests.

Task 1.2: Gas cleaning system
The gas from the ACFBG is first cooled, and then cleaned in a filter unit to remove ash and other solid impurities from the product gas. The selection of the filtering media is critical, because it has to tolerate high temperature and resist the attack of alkalies and other aggressive components in the gas. In atmospheric conditions, small pressure drop over the filter is of primary importance, too. In the pilot test, one material has been tested with great success. The performance of the filter was monitored during the tests by measuring the dust content in gas before and after the filter. The pressure drop over the filter was measured continuously. Cleaning of the filter material by pulsing was also tested. After the tests, the filter materials have been inspected and analysed for physical or chemical damages. No damages were found.

Task 1.3: Gasification test with loose straw
In the gasification test, loose straw was gasified. The gasification process was optimised in respect of the overall process performance, including stability and gas quality. The amount of sand and other bed additives were tested and minimised. Under the tests process data were logged continuously and the gas composition was analysed semi-continuously. A specialised research laboratory carried out special samplings and analyses, like tars.

3.3 WP 2: Design study (100 MW_{th})

The tasks cover plant sections of different technical maturity and includes preparation of overall layout, fundamental plant concept and the corresponding required scope of supply, main data, description of operational properties and mapping of all emissions, residues and noise. The tasks also include preparation of time table and plant budget, so extensive that it can form a basis for a final decision to built a demonstration plant.

Task 2.1: Comprise fuel feeding, air preheating, gasifier, ash removal system, gas cooling, gas cleaning system and gas connection components
These systems, which primarily represent non-proven technology due to the straw fuel, are worked through and evaluated technically as innovative elements.

Task 2.2: Electrical systems
Represent well proven technology, which will be covered by the normal basic and conceptual design.

Task 2.3: Comprises the C&I system
The premises and logistics for the system are non-standard. A preliminary operation procedure analysis has been prepared to determine any critical events, procedures and plant configurations that should be taken into consideration during the detailed design, to ensure the safe and proper operation of the plant. The analysis is concentrated on normal start-up and stop procedures as well as disturbances and secure viable and steady operational properties.

Task 2.4: Buildings
Represent well proven technology, which will be covered by the normal basic and conceptual design.

4. PROCES VALIDATION

4.1 Introduction

The first gasification test in FWE´s pilots was carried out in spring 1999. The fuel was pelletised straw. The main objectives of the tests were to scope the conditions for gasification, gas cooling, dust separation and gas combustion. The test plans and process conditions were based on preliminary testing with straw by VTT in their PDU gasifier. In the tests, it was confirmed that pelletised straw could be gasified in spite of its high alkali contents and low melting point of the ash.

In the second gasification tests during the winter 1999-2000 loose straw was gasified. The newly developed straw feeding system was also tested in practice. The synthesis gas was cleaned in a new baghouse filter before combustion. In these tests it was confirmed that also loose straw can be successfully fed into gasifier and gasified to produce a steady flow of combustible gas. The ranges of applicable process conditions were found. It was however obvious that certain modifications to the equipment must be done. It was also concluded that a third gasification test with loose straw was necessary to validate the results of the previous tests, i.e. performance of the straw feeding system, optimal process conditions and performance of the gas cleaning system. This work was completed in the STRAWGAS project with the financial support from EU.

Description of the Pilot plant

The 3 MW_{th} CFB gasifier pilot plant used in the tests is shown in Figure 4.1.

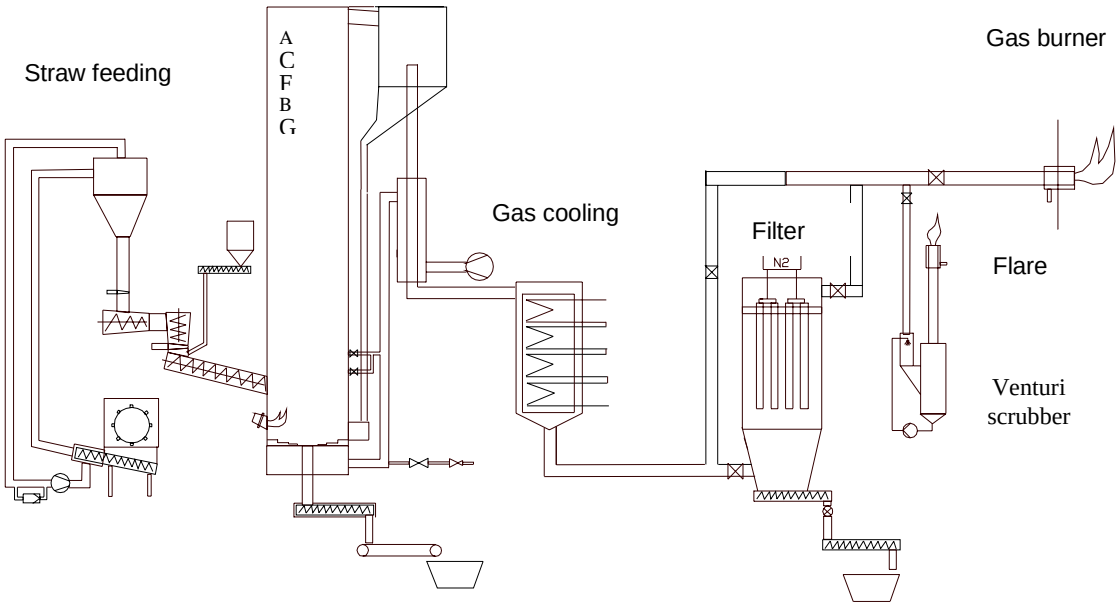


Figure 4.1. Flow scheme of the 3 MW_{th} atmospheric CFB gasifier pilot plant

The pilot plant is briefly introduced above in Chapter 4.3.1. The main dimensions of the equipment are shown in Table 4.1.

Process	Atmospheric circulating fluidised bed gasifier
Year of construction	1980, modified 1997-1999
Reactor diameter height	 600 mm 10,0 m
Operating temperature Gas-flow velocity in the reactor Air-flow rate Operating pressure Fuel feed rate Thermal capacity Gas cleaning Gas combustion	600-1000 ^{o} C 1.5-6 m/s 0-0.25 Nm³/s 100-140 kPa 0-1000 kg/h 3 MW Hot filter bag house Venturi scrubber Product gas burner Flare

Table 4.1. Technical details of the ACFBG-gasifier

4.2 Development and optimising of the straw feeding system

In this chapter the process of designing and building a straw delivery and feeding system is described. The system has been mounted on a 3 MW fluidised bed gasifier and has been operating for approx. 500 hours in total.

4.2.1 Determination of mechanical straw properties

Prior to the design and building of the straw feeder described in this chapter, a national Danish R&D project concerning identification of relevant mechanical parameters was carried out.

The purpose of this project was to establish the basic mechanical data for straw, and hereby improve the basis for designing plug feeders for straw. The data from this work is described in Danish. “Mekaniske basisdata for halm” (English title: "Mechanical data for straw"). This report includes a comprehensive description of the literature concerning feeders and mechanical data for biomass, as well as experimental data from a series of tests conducted by the authors. Friction is investigated by pressing straw against a moving surface. Ratio of cross contraction, defined as the ratio between axial and radial tension, is calculated in a mathematical model by using measured data for friction against a plane surface and friction of a plug in a tube. Compressing straw in a cylinder, and establishing corresponding values of density and applied tension investigate compressibility. Gas permeability is investigated by measuring corresponding values of air pressure drop and airflow. All tests have been made with straw with a density from 300 to 1200 kg/m^3 and humidity from 9 to 25%.

Coefficients of friction have been found between 0,17 and 0,25, with a tendency to decrease with increasing density. And as a result, increased pressure on surfaces. And increased moisture content shows a reduced friction. Ratios of cross-contraction have been found between 0,45 and 0,65. The tests with gas permeability have shown that it is possible to produce a plug feeder (1 ton/h), for a vessel at moderate overpressure (100 mbar) with a gas leak rate of 10 l/min at a density of 500-700 kg/m^3. It is possible to obtain leak flows as low as 0,01 l/min at a density of 1050 kg/m^3. It’s concluded that the experimental work combined with the modelling, represents an improved basis for designing plug feeders for straw.

4.2.2 Technical Background

TK Energi has worked with design and building of feeding screws for straw and other types of biomass since 1989. Several screws with capacities from 2-500 kg pr hour up to 10-20 tons per hour have been designed and built, and a more research orientated project concerning development of methods for mechanical characterisation of biomass has been carried out. Before this design work was started, 2 screws in the relevant size have been designed and built. One screw has been used for parameter studies, and one has been feeding into a gasifier in another project. Both screws have worked without problems. Both screws have been designed from ordinary construction steel as they where not designed to operate for thousands of hours. The screw used for parameter studies has been operating approx. 280 hours. According to the information about the number of operation hours for the other feeding screw, it has operated approximately 700 h. There has not been detected any significant wear on any of these 2 screws.

4.2.3 Design criteria

The screw for this project was designed to a capacity of 1000 kg straw pr hour. A detailed technical discussion of the technical parameters is done in the previously published report "Mekaniske basis data for halm" (English title: "Mechanical data for straw").

4.2.4 The plug feeder

A sketch of the plug feeder is shown in figure 4.2 below.

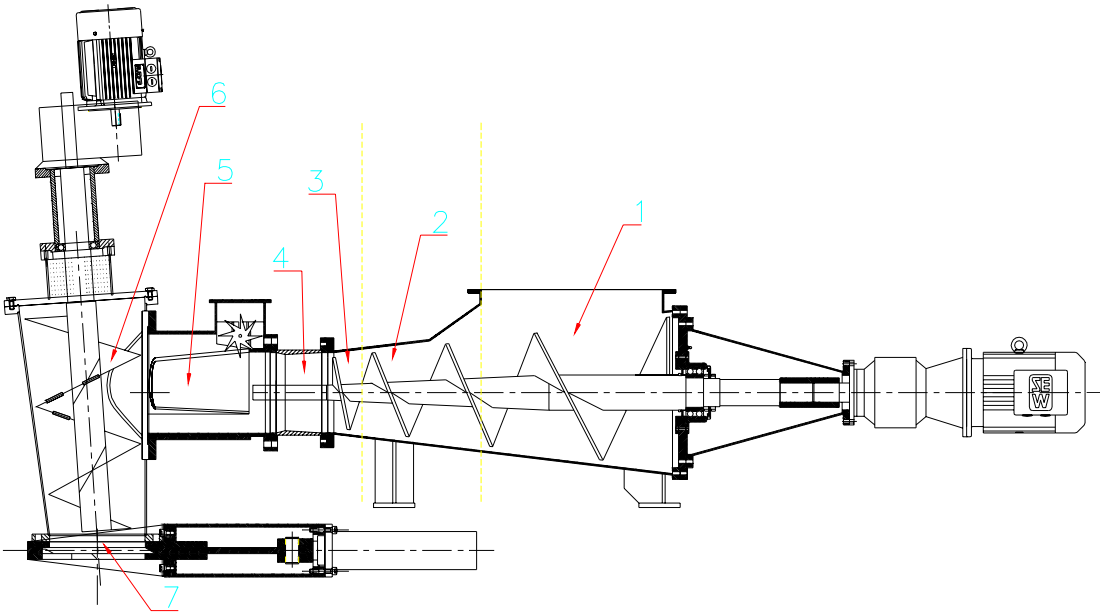


Figure 4.2 Functional feeder sections: (1) filling section, (2) pre-compression section, (3) final compression section, (4) sealing plug section, (5) sealing control section, (6) plug chopper, (7) fire valve

The feeding screw take care of 3 functions, filling, precompression and final compression. In the filling section of the screw, the straw is filled into the screw without any compression. In this section the design density in the screw should be 10-20 kg/m^3.

In the precompression section, the straw is compressed from density in section 1 to about 100-150 kg/m^3. The outlet of section 2 defines the capacity limit of the screw.

The final compression section consist of the last turn of the screw. The straw is compressed from the outlet of section 2 to the density in the sealing zone. This is, for the present screw, estimated to be approx. 350-500 kg/m^3.

The basic idea of the sealing principle is continuously to put straw into a pipe and maintain the total resistance against movement constant and consequently creating a sealing plug. The screw feeder creates the desired axial force, and the total friction in sealing and the sealing control section obtains the desired resistance force.

When designing the sealing plug section following parameters have to be considered:

- The leak rate of the seal
- The controllability of the seal
- The energy consumption and subsequently the wear of the sealing plug section

The leak rate is defined by the requirements of the process where the feeder is feeding into. The desired leak rate is obtained by compressing the biomass to the density where this leak rate is obtained.

The controllability of the sealing is the ability to maintain a stable and tight sealing and to avoid blockage of the sealing in operation conditions that will occur when handling the material that has to be fed, e.g. variations of moisture content in the biomass. If the total friction of the sealing plug section and the sealing control section is too small to maintain a plug, the sealing will be blown out. Blockage of the sealing occurs when a friction lock is created. The sealing can be blocked when the total friction is larger than the pressure that can be applied to the sealing. In this case, it can happen that the increased friction of the sealing plug as a function of the increased pressure on the sealing, creates the friction to block harder.

A low wear is of major importance for the construction of the sealing plug section. As a rule of thumb, the wear is proportional to the surface pressure on the relevant surface.

The function of the control mechanism is to maintain the seal in all operation conditions. This is done by keeping the complete friction of sealing plug section and the sealing control section constant, or as constant as possible.

4.2.5 Design of feeding auxiliaries

In order to obtain a texture that is suitable for further processing in the gasifier it can be necessary to break or chop the sealing plug. The plug chopper is a screw conveyer placed perpendicular to the plug. The screw scrapes the plug and consequently divides the straw and transports it further in the system. The screw is mounted with a 4 kW gear motor and it rotates 125rpm.

A fire valve is constructed to shut off the access from the feeding system, to avoid burn back in the feeding system. In order to make sure that the valve closes in all cases, it is designed to cut a 20 mm steel round bar, or a 150*150 mm piece of oak. An accumulator is mounted in the hydraulics. This gives enough pressure to shut the valve in case of power failure.

Figure 4.3 The plug feeder system connected to the pilot CFBG

4.2.6 Control strategy and mechanical properties in the straw plug

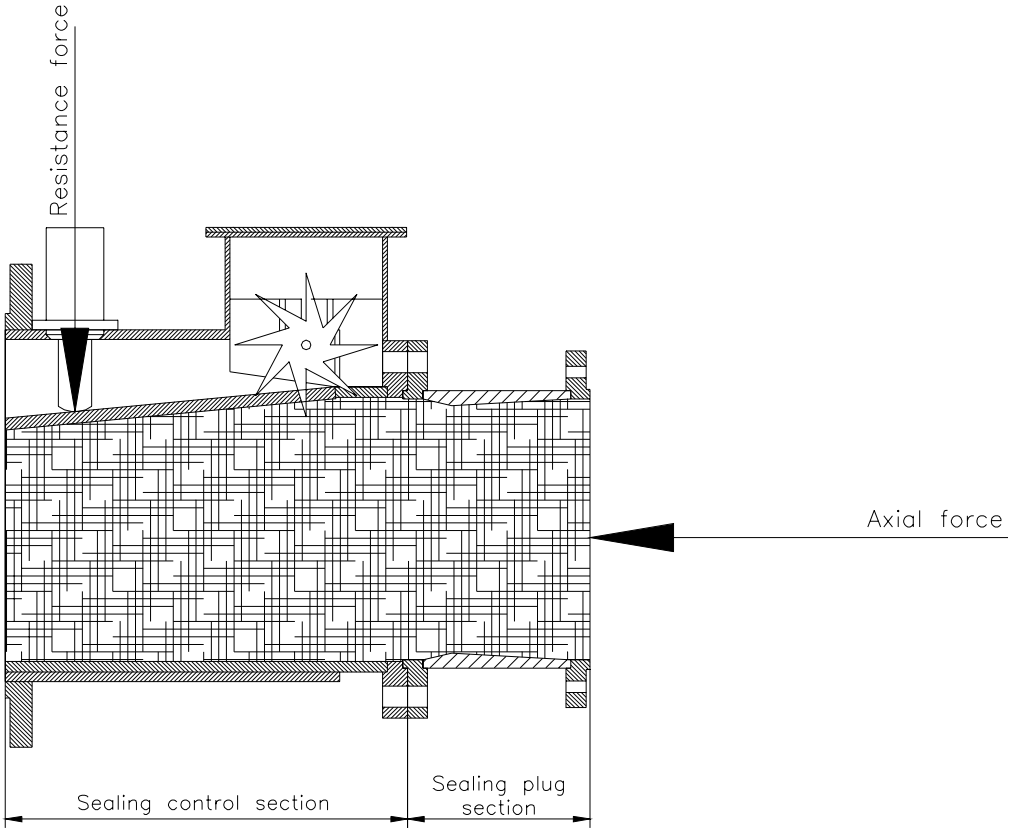


Figure 4.4 Principles of sealing control mechanism.

Basic ideas

The basic idea is to create a gas tight straw plug sealing. Pressing straw into a sealing plug section using the "axial force" for this. To create the axial force, a resistance force is needed. The purpose is to obtain a density that gives the necessary tightness. The feeding screw creates the axial force and a retaining mechanism creates the resistance force. The

purpose of this mechanism is to adjust the density to withstand a tight sealing plug that is able to move. Higher density means higher axial force, better sealing, higher power consumption and wear.

The straw fiction
The axial force must overcome the total friction forces in the sealing plug and sealing control section. A control of the resistance force will keep the total friction forces almost constant. The friction in the sealing plug section will vary with straw density, moist content and other physical properties.

At low density a high moist content gives lower sealing plug friction. At high density it is opposite. The variation of the friction coefficient is normally not very large with "good quality" straw at densities below 300 kg/m³. But at 300-600 kg/m³ large variations can occur at *very slight* difference in the parameters. At higher densities the variation can be much larger.

In theory the resistance force should be constant and give a constant density, if the straw have constant mechanical properties. But the physical property varies with density, moist and straw type. Consequently a control of the sealing plug resistance is necessary to keep a stable plug.
A set point is chosen and the control gives an output controlling the hydraulic pressure in the sealing control section.

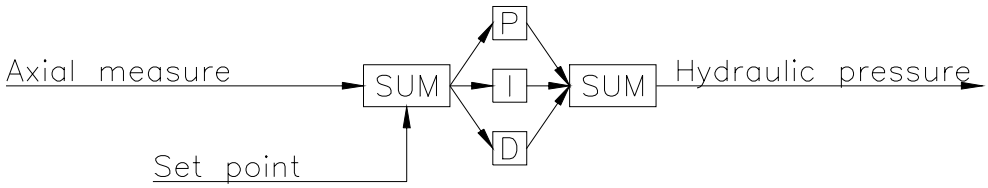


Figure 4.5 Principles of PID regulator

The purpose of the control is to keep the density in the sealing plug constant no matter what physical properties the straw or any foreign matter that might be in the straw. Consequently it is necessary to control the hydraulic pressure. A PID controller is adapted to fulfil this.

4.2.7 Pneumatic transportation system

A pneumatic transportation system was built to bring the straw from the disintegrator to the plug feeder. See figure 4.7. This system was chosen because of the flexibility and price. Several other solutions were evaluated like conveyor belts, screws etc.

A 15 kW, 3000-RPM fan with a "self cleaning" rotor was bought and tested. The first idea was to inject the straw into the fan inlet. A test was carried out, but showed that the straw was chopped too much passing trough the fan. Therefore it was decided to construct an arrangement where the straw doesn't pass trough the fan.

Several experiments were carried out to see how to inject the straw into the system. It was discovered that injecting straw with ejector and other similar devices was very difficult when the fan was placed to create an overpressure system.

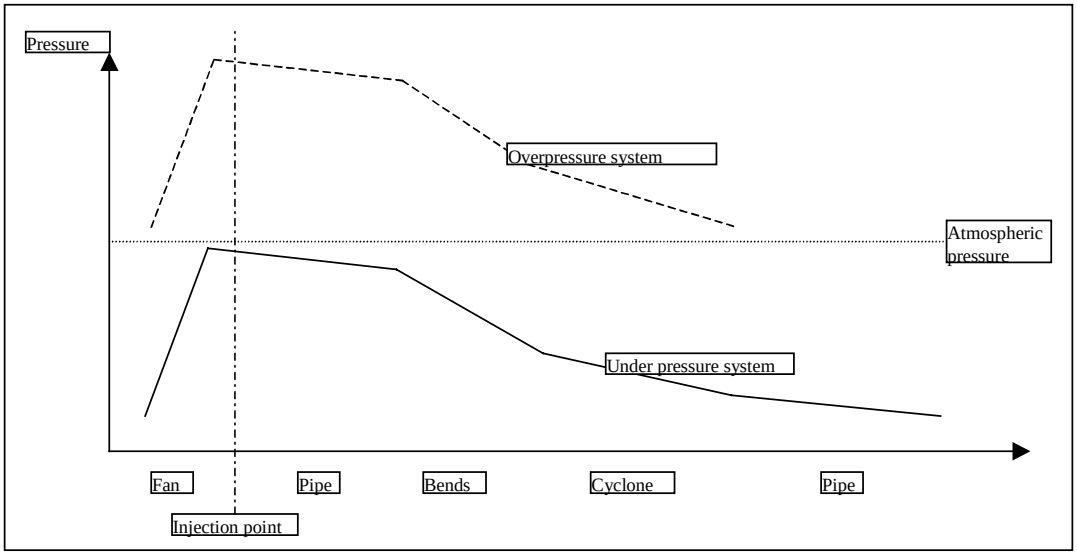


Figure 4.6 Pressure in pneumatic transport systems.

An under pressure system with return air was proposed, and an ejector for straw injection was designed and tested.

To maintain the under pressure in the system, part of the transport air is blown out just before the injection point, this gives atmospheric pressure at the straw injection point. The sketch above shows the development of pressure trough out the two systems.

Figure 4.7 shows an under pressure system. Only at the air outlet is there a slight over pressure. The negative pressure in the bottom of the cyclone has been measured to 30-35 mm WG.

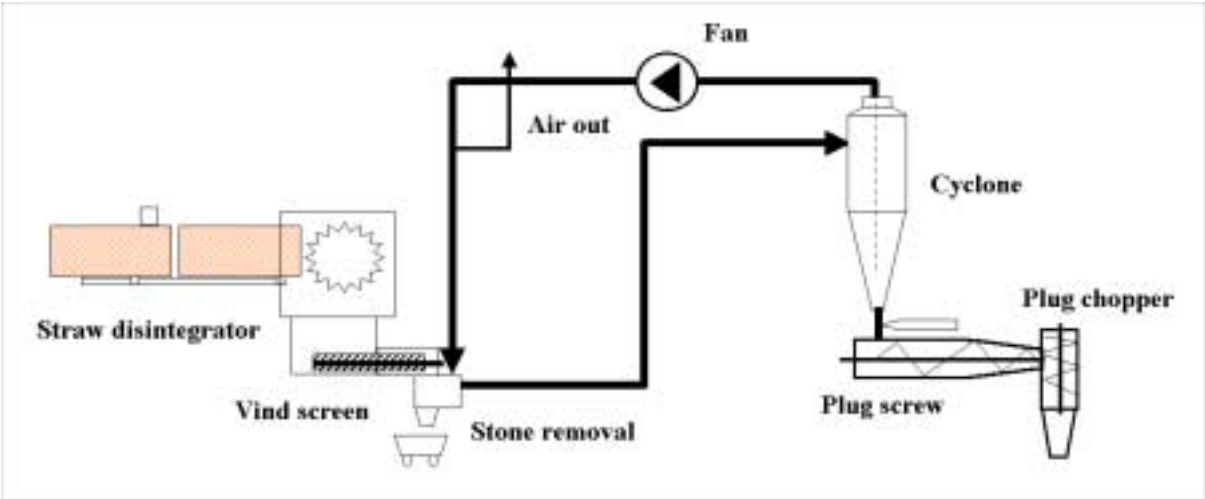


Figure 4.7 Pneumatic transport system

4.3 Gasifier and gas cleaning system

4.3.1 Gasifier

The refractory-lined gasifier reactor is inside a 10m high gas-tight steel shell. The straw fuel is transported pneumatically, as described in Chapter 4.2, and fed into the circulating fluidised bed reactor. The bed is fluidised by preheated air flowing through the air distribution grid at the bottom of the reactor. Air is fed in by a Roots blower, the capacity of which is 0.25 m^3/s of 1.4 bar air. The coarser solids, entrained from the reactor, are separated in a cyclone and recycled back to the bottom of the reactor. Circulating material can be sampled at the bottom of the return leg.

Bottom ash is discharged from the reactor by a vertical pipe, which is transporting ash to a water-cooled screw. In the screw, ash is cooled to 100-200 ^{o}C. The screw is unloading ash to a drag-chain conveyor, which is taking it to an ash storage bin. The bottom ash sampling tube is located at the bottom of the ash removal duct.

The hot product gas, leaving the reactor at 700-850 ^{o}C, is cooled in the gasifier air preheater to 600-700 ^{o}C. The product gas is cooled further in the water-tube boiler, which is able to operate with maximum water values of 60 bar and 240 ^{o}C. After the boiler, the gas is cleaned in a hot bag house type of filter unit. After the hot filter, the product gas is led optionally to combustion or into a Venturi scrubber to be finally cleaned from the dust. After the Venturi scrubber the gas is burned in the stack-flare supported by natural gas, placed at the top of the stack at the height of 33 m. To examine gas combustion, product gas was burned in a small 500 kW combustor and in a 2.0 MW_{th} combustor.

4.3.2 Hot filter and other gas cleaning equipment

The hot product gas from the gas cooler is filtered in a bag house filter by a new type of high temperature filter material CG18 manufactured by 3M. The filter bag manufacturer was Fasse Filter Productions GmbH. The hardware supplier for the bag house type of filter unit was W.L. Gore & Associates (UK) Ltd.

The type of the 3M filter material was a woven glass fibre bag, which has been coated to give durability and maintain the filtration properties up to 482 ^{o}C. The glass fibre is a textile grade, i.e. high purity silica fibre with an average diameter of 6.5 microns. The inorganic coating enhances the dynamic mechanical properties of the fibre, providing the fibre bag with improved high temperature performance.

To decrease the uncertainties regarding the filter operation noticed in the previous gasification tests (risk of damage due to smolder of carbon on filter surfaces), some changes at the inlet of dust-loaded gas into the filter were arranged. New assembly delivers the raw gas more evenly and directed downwards into the filter.

The design conditions for the filter material and unit were as follows:

- Gas to be filtered: Product gas from the gasifier
- Volumetric flow: 3600 m^3/h
- Temperature range: 350-400 ^{o}C, max 450 ^{o}C
- Particle concentration: Maximum 50 g/nm^3 at the inlet

Dimensioning of the filter was executed as follows:

- Number of bags: 6X10 bags all together
- Pulse cleaning: Nitrogen
- Cleaning device: Sonic horn
- Operational pressure drop: 500 – 1500 Pa

In normal conditions, the dust concentration in the product gas was less than 100 mg/Nm³.

Fly ash from the bottom of the hot filter is discharged optionally to 150-l barrels or ash container by two transporting screws. A rotary valve is located between the screws. Sampling of the filter ash is carried out at the outlet of the 2nd ash screw.

After the hot filter, the cleaned gas was led to:
- 500 kW_{th} combustor
- 2 MW_{th} combustor
- Flare

The gas combusted in the flare was first washed in a Venturi scrubber. The scrubber and flare serve also as a filter by-pass for the total gas flow in case of malfunction of the filter or gasification process.

The Venturi scrubber consists of a straight constant-diameter washing pipe spraying the water at 5-10 bar pressure into the gas flow. After the pipe, the gas-water flow is led as a tangential flow into a separating tower. In the tower, water droplets hit the walls and flow to the bottom of the tower while the gas exits the tower to the stack and flare.

The scrubber system also includes two tanks for water circulation and a separation tank for separation of tars from the water. The system is separating tar components to the surface of tank 1, from which an overflow is led through a fabric filter to the local sewer.

4.4 Gasification test with loose straw

4.4.1 Sampling and analysis

During the tests, solid samples were taken from each one of the test equipment so that the sampling frequency was typically 1 sample every 2-4 hours. The fuel samples were taken from every third bale, once every 3 hours. The samples of each test were collected in containers, mixed and divided into samples for analyses and samples for later storing. All the fly ash from the gasifier was stored in barrels for further testing.

Sample types are explained in table 4.2.

SAMPLE TYPE	SUBTYPE	LOCATION
ADDITIVE	limestone and bed sand	feed bin
BOTTOM ASH	-gasifier	in the BA duct
CIRCULATING MATERIAL	-gasifier	return leg
FLY ASH	-gasifier	3M hot filter bag house
FUEL	-gasifier	straw bales
WATER	-gasifier scrubber	tanks and sewer
DEPOSIT	-gasifier	various places

Table 4.2 Solids sampling in tests with straw

The product gas composition of CO, H_2, CO_2, CH_4, C_2H_4 and C_2H_6 was analysed automatically by a gas chromatograph. For safety reasons, the concentrations of H_2 and CO

in the reactor room were monitored by on-line analysers. These were connected to the process control system and defined as locking parameters, which would shut the plant in case the threshold concentrations were exceeded. Two CO analysers were also mounted above the product gas pipe before the CFB boiler. O_2, CO, SO_2, NOx and HCl concentrations in the fluegas after the product gas combustor were also measured.

The gas analysis equipment is collected in Table 4.3.

In selected test runs, VTT sampled and analysed:
- amount of tars in the product gas
- composition of tars
- ammonia and HCN concentrations in the product gas
- HCl and Cl_2 concentration in the product gas
- fly ash concentrations in the product gas
- composition of fly ash
- product gas moisture

University of Kuopio analysed from three filter ash samples:
- chlorinated phenols
- benzene's
- PCB
- PAH
- PCDD/PCDF

ACFBG				
O_2	Servomex	0-25%	dry	before boiler
CO	Uras	0-1000ppm	dry	before boiler
CO	Uras	0-50%	dry	before boiler
O_2	Servomex	0-25%	dry	after boiler
H_2,CO,CO_2, CH_4,C_2H_4,C_2H_6	GC	0-100 vol.-%	dry	before hot filter
CO	TECO	0-1000 PPM	dry	in duct before plug feeder
Product gas burner				
SO_2	ML	0-500ppm	wet	after pgb
NO_x	ML	0-500ppm	wet	after pgb
CO	Uras	0-1000ppm	dry	after pgb
CO_2	Uras	0-20%	dry	after pgb
O_2	Servomex	0-25%	dry	before boiler
O_2	Rosemount	0-10%	wet	after boiler
N_2O,CH_4,CO_2	FTIR		dry	after boiler
HCL	Servomex	0-600ppm	wet	after boiler

Table 4.3 Gas analyses and continuous gas analysers in straw tests

4.4.2 Program of the gasification tests

The preparations for the test were started in May 2000. After a number of minor modifications and improvements of the equipment, cold scoping tests were carried out during the week 20/2000 (15. -19.5.2000) before the start of the test program. In the tests, the process was tested by operating motors of all equipment. A major attention was focused on the straw feeding devices. They were tested by letting big amount of straw comparable to test run conditions enter through the system. Most of the feeder tests were done between May 17 and 18.

The final program of the gasification test is shown in Table 4.4. Test Run No 5 was not stable and was excluded from the Table.

Week of 2000		W21	W23	W24	W35	W35		W35
Run		1	2	3	4	6		7
Start	dd.mm.yy hh:min	23.05.00 04:00	05.06.00 20:10	13.06.00 19:00	29.08.00 00:20	31.08.00 00:00		31.08.00 18:00
Duration	H	28.5	63.5	60.4	25.2	14		10.5
Straw	Year	1995	1997	1997	1997	1997	wood	1997
Temperature	^{o} C	806	807	821	817	828		824
Fuel	kg/h	606	591	528	588	499	105	600
Fuel	g/s	168	164	147	163	138	29	166
Air	g/s	190	184	166	187	210		190

Table 4.4 Main parameters of the STRAWGAS gasification tests of loose straw

During the week 21/2000 start-up and shut-down procedures were tested and the preferred procedures were defined.

The long Run No 2 during the week 23/2000 was split into two parts, due to failures in the filter ash screws and reactor screw of the fuel feeding system in the middle of the week.

Higher gasification temperatures were tested during the week 24/2000.

During the summer a separate feeder system for wood chips was constructed. The possibilities to use some new additives were discussed. The testing was continued in August during the week 35/2000. After tuning the gasification with straw (Run 4), wood chips and straw were co-gasified in Runs 5 and 6. The first test run No 5 with wood chips and straw was unstable, and it was later cancelled. In the last test run No 7, dolomite/sand mixture was used as bed make-up material.

4.4.3 Fuels and additives

Danish straw from 1995 and 1997 harvests was used as the main fuel. Wood chips were purchased locally. Wood chips consisted of a mixture of pine and spruce.

Bed make-up was used to maintain the bed inventory. The bed make-up was a 50/50 mixture of Finnish limestone and sand. In the last test run No 7 dolomite was used instead of limestone.

Steam injection into lower furnace was used for bed temperature control when necessary.

The fuel analyses are shown in Table 4.5. The straw alkali and chlorine contents vary considerably. Therefore, the analyses results were confirmed by calibrations and repeating the K and Cl analyses. The lowest measured chlorine concentrations (130- 230 mg/kg) are exceptionally low for straw. The analyses of bed additives are shown in Table 4.6.

TEST RUN			RUN 1	RUN 2	RUN 6
Fuel			straw	straw	wood
Year			1995	1997	2000
Proximate analysis					
Moisture	as received	%	12.1	11.4 – 14.0	53.9
Volatiles	in d.s.	%	81.4	78.8 -80.4	84.8
ash, 815°C	in d.s.	%	3.2	3.4 -4.7	0.67
ash, 575°C	in d.s.	%	2.9	3.5 – 5.1.	0.60
fixed carbon	in d.s.	%	15.4	15.4 –18.2	14.6
Ultimate analysis					
C	in d.s.	%	47.8	46.7 - 47.6	50.3
H	in d.s.	%	5.89	5.67 –6.05	5.89
N	in d.s.	%	0.51	0.52 – 0.74	0.05
S	in d.s.	%	0.06	0.07 – 0.12	0.01
O	in d.s.	%	42.5	41.7 – 42.5	43.2
Heat values					
HHV	in d.s.	MJ/kg	19.05	18.61 – 18.85	20.24
LHV	in d.s.	MJ/kg	17.76	17.32 – 17.61	18.95
Halogens					
Cl total	in d.s.	mg/kg	230	130 – 5520	< 100
Alkaline					
Na, total*	in d.s.	mg/kg	30	< 20	70
K, total*	in d.s.	mg/kg	3310	3640 - 10860	580

Analyses are made of combined fuel samples. Sampling in each test run from every third bale, approximately every 2.5-3 hours.

Table 4.5 Analyses of fuels

XRF-analysis		Dolomite	Limestone	Sand
Main components calculated as elements				
Na	%	0.0	0.0	2.4
K	%		0.1	2.7
Ca	%	21.7	39.8	2.0
Mg	%	9.8	0.7	0.4
Al	%	0.5	0.0	6.7
Si	%	3.8	0.2	35.0

Table 4.6 Analyses of bed additives

4.4.4 Process conditions in gasification

Due to the sensitivity of the fuel and fuel ash, the process conditions, such as temperature, were changed in quite narrow ranges. The intention was to keep the process stable and not aiming at existing limits to form a complete bed sintering. The air ratio of gasification was about 0.2, except in test No 6, where wood and straw were co-gasified. Due to the high moisture of the wood chips, air ratio 0.3 was required for acceptable process performance.

The heat value of the wet gas varied from 5.18 to 5.65 MJ/Nm³ in straw gasification. In co-gasification of wood and straw, the heat value of the gas was lower, 3.92 MJ/Nm³.

The gas composition, as shown in Table 4.7, was quite steady. No dominating correlation's of gas composition to any of the process parameters in the used range was found.

Run		W21/1	W23/2	W24/3	W35/4	W35/6	W35/7
Fuel		straw	straw	straw	straw	str.+w.	straw
Fuel Feed rate	g/s	168	164	147	163	167	166
Air feed rate	g/s	190.0	184	166	187	210	190
Energy input	kW	2656	2646	2295	2467	1983	2604
Gas calorific value, wet	MJ/Nm³	5.51	5.65	5.47	5.43	3.92	5.18
Gas calorific value, dry	MJ/ Nm³	7.25	7.54	7.36	7.19	5.15	6.90
Gas composition, dry							
CO	mol-%	15.00	16.5	16.33	15.23	14.00	14.71
H2	mol-%	8.80	8.20	7.10	5.96	7.58	7.54
CH4	mol-%	4.73	4.96	4.87	4.72	4.58	4.88
C2H6	mol-%	0.20	0.25	0.17	0.15	0.17	0.14
C2H4	mol-%	1.61	1.87	1.70	1.78	1.76	1.86
CO2	mol-%	16.42	15.85	15.21	15.18	17.05	17.55
N2	mol-%	53.00	51.80	52.9	53.15	54.35	53.99
NH3*	mg/ Nm³		1765	2480	1930	1410	
HCN*	mg/ Nm³		195	550	525	200	
Tars*	mg/ Nm³		11126	11456	10796	8074	
Benzene*	mg/ Nm³		8500	8000	7914	6520	
Temperatures							
Reactor	°C	806	807	821	817	828	824
After hot filter	°C	316	319	315	329	328	327

*Balance border: after air pre-heater

Table 4.7 Measured and calculated process parameters

4.4.5 Total mass balance

Material and energy balances were calculated for gasification test runs 1-7 of Danish loose straw. The balance calculation takes into account:

- 7 main gas compounds (CO,H_2,CO_2,N_2,H_2O,O_2,CH_4)
- 5 gaseous light hydrocarbons
- Benzene and 7 tar compounds.

All balance calculations were carried out based on those time periods during which VTT had carried out measurements, and otherwise at the time of the most stable process conditions. It should be noted, that the calculations are based on measured average rates. The fuel feed rate was determined by calculating from bale weights and loading times. The measuring devices were calibrated before the test runs.

4.4.6 Ash balances and carbon conversion

The ash balance was determined based on the measured ash flows out from the process. Input of fuel ash was calculated from the fuel analyses. Calcination degree of limestone was also taken into account.

The closure between the input and output values was within 100±10% for most of the balances.

The energy loss caused by the unburned carbon in ashes is calculated by using the following heat value:

$C + O_2 = CO_2$ q = 32.77 MJ/kg C

The carbon content in bottom ash was very low, and consequently, the energy loss in bottom ash was insignificant. Hence, nearly all of the energy loss is due to the unburned carbon in filter ash.

The carbon conversion to gas and tars was from 93.8% to 97.2%.

4.4.7 Alkali and chlorine balances

The calculation of the alkali balances was based on the measured input flows, weighed and calculated ash streams and analysed compounds of the input and output streams. Alkali metal compounds in vapour phase were not determined due to the fact that the levels were earlier proven to be very low.

Most of the alkali in straw is potassium (K), and only the potassium balance is reported here. The amount of sodium (Na) is only a few percent of the total alkali in the fuel, see Table 4.5.

Most of the alkali (K) escaped to filter ash.

The chlorine balance was based on the measured input flows, weighed ash streams and analysed compounds of input and output streams. The fly ash samples were taken from the barrel placed under the hot filter. The fly ash chlorine concentrations used in the mass balance calculation based on XRF-analyses.

VTT took samples of vapour phase chlorine from the cooled gas after the filter by probe technique. The gas temperature was approximately 340-360°C. The chlorine concentrations of vapour phase were low, they varied from 5 to 15 ppm in week 23, and they were < 5 ppm in week 24 and in week 35.

The chlorine was captured nearly quantitatively in the bag house filter ash, evidently as KCl.

4.4.8 Conversion of fuel nitrogen

Both, HCN and NH_3 were analysed from the gas samples taken by VTT. About 47 - 68% of the fuel N was converted to ammonia and 3 – 10% to HCN.

4.4.9 Toxic compounds

University of Kuopio analysed three combined fly ash samples from the test runs. The compounds analysed were:

- chlorophenols (Cl-Ph)
- polychlorinated benzenes (Cl-Bz)
- biphenyls (PCB)
- polycyclic aromatic hydrocarbons (PAH)
- dioxins
- furans (PCDD and PCDF).

The concentrations of Cl-Ph, Cl-Bz and PCB were very low or below the detection level.

Components	ng/g
Chlorophenols	10 –20

Chlorobenzenes	4 – 7
PCB	Not detected
PAH	98,7 mg/kg
	pg/g
PCDD (total)	0 – 8
PCDD (I-TEQ)	0
PCDF (total)	0 – 38
PCDF (I-TEQ)	0

Table 4.8 Toxic organic components in filter ash

It could also be concluded, that dioxins and furans are not significantly formed in the conditions of the loose straw gasification. PCDD and PCDF in fly ash was 0 pg/g expressed as toxicity equivalents according to I-TEQ (2,3,7,8-TCDD has a toxicity coefficient = 1).

The PAH concentrations were about 100 mg/kg, which can be classified as high but not exceptional. The values are anyhow too high to meet the Danish legislation (PAH < 3 mg/kg).

The measured concentrations of tars are shown in Table 4.7. In straw and wood co-gasification, the gas contained about 8 g/Nm³ tars. During straw gasification, the tar concentrations were higher, about 11 g/Nm³. The most abundant tar components were naphtalene and toluene (about 2 g/Nm³ each in straw gasification). The benzene concentrations were, correspondingly, about 6.5 and 8.2 g/Nm³.

The tars and benzene were not condensed during gas cooling and filtration, but they were burned together with the gas, increasing the heat value of the gas by 10-20%.

4.4.10 Performance of the gas cooler

The product gas was cooled in the water-tube boiler, which consisted of two parallel passes. One pass was cleaned with a conventional rotary soot blower with steam. The other pass was cleaned with a Foster Wheeler Spring hammer cleaning device.

The cooling elements were inspected and deposits sampled after each test week. After the tests, 1-2 mm thick dark layer of condensed tar and ash -based deposit was found on the surfaces of the tubes. A tar and ash layer of 2 mm could be found in the coldest part of the cooler, that is the lowest heat element, where the gas temperature was around 350-450 ^{o}C. A tar layer of 1 mm was found on the first heat element, with gas temperatures around 550-680 ^{o}C. No signs of corrosion were found on the cooling tubes.

Visually the cooler deposits were brittle and formed by condensed tars, but the analyses indicated that carbon content was not very high in all of them, so there must have happened sticking of ash particles and tars together.

4.4.11 Deposits in the gasifier

The gasifier was inspected thoroughly after each test week. All deposit formation was sampled.

The elementary composition of deposits was analysed by a semi-quantitative XRF-analysis. In the gasifier deposits were seen to be only in two places; in the duct between the riser and the hot cyclone and in the hot cyclone. The hot cyclone deposits consisted of layers of alkali-containing sand, which had formed on the bottom of the cyclone, probably due to a slowing of particle flow near the cyclone wall. The deposits were not serious to the gasifier performance.

4.4.12 Gas combustion

Part of the gas was combusted in a 500 kW_{th} combustion chamber and part in a 2 MW_{th} combustor. The combustors were operated by gasification gas supported by a small natural gas flame.

The flue gases from the smaller combustion chamber were analysed in details. The product gas input was about 425 kW and the natural gas input about 5 kW. All the measured emissions were low. See Table 4.9.

Run		W23/2	W24/3
Flue Gas Composition		Average	Average
Fuel sensible heat	kW	57.8	55.3
Gasifier gas	kW	323	315
Natural gas	kW	5	5
Combustion temperature	^oC	884	793
SO_2 after burner (wet)	ppm	4	7
O_2 after burner (dry)	%	10.96	12.14
NO_x after burner (wet)	ppm	160	175
CO After Burner (dry)	ppm	20	18
CO_2 After Burner (dry)	%	7	7

Table 4.9 Emissions from the product gas burner

4.4.13 Conclusions of the gasification test with loose straw

In the STRAWGAS project, the main objectives were to validate:

- The capability of the developed feeding system to feed loose straw into the reactor of the ACFBG pilot plant
- The optimal process conditions and additives for the ACFBG gasifying loose straw
- The capability of the selected gas cleaning system and filter material(s) to separate ash and other solid components from the gas, to make it suitable for co-combustion in large CHP plants

For the validation, a gasification test was carried out. The total number of test runs was six. 21/2000 was dedicated for start-up and shut down tests. Weeks 23 and 24/2000 included both one long test run. In week 35/2000, tests with different bed materials, and a test of co-gasification of straw and wood chips was done.

Total time of gasification was about 210 hours, of which 125 hours in two long runs. In total 120 tons of straw was converted to combustible gas.

Based on this test program, the following conclusions can be drawn:

- Loose straw was successfully gasified in a 3 MW_{th} CFB Pilot Plant
- Smooth, stable operation in spite of high alkaline fuel was achieved
- Optimal temperature could be reached to ensure good carbon conversion
- Steam injection was occasionally needed to control the bed temperature
- Wood and straw could be gasified together and trouble-free operation was reached
- Bed make-up was required to keep the bed inventory
- Carbon conversion could be kept still in the range of 95 - 97%, compared to 90% with pelletised straw
- 3 M's Filter operated well without blinding by tars and it removed also alkalis and chlorides quantitatively at 350...370°C from the synthesis gas
- In the gasification conditions, PAH were formed, dioxins and furans were not formed
- The optimal gasification conditions were validated in the project

4.5 Treatment of filter ash

In the straw gasification process, a significant amount of filter ash is formed, and shall be treated. A disposal of this ash is problematic due to its composition, especially due to a high, 20-40%, contents of unburned carbon and PAH in the ash. For example, this ash could not be recycled back to the fields or dumped in the dumping grounds. The ash disposal is a real key issue in CFB gasifiers.

Due to the crucial importance, Foster Wheeler Energia Oy decided to test, on its own cost, oxidation of fly ash as a potential solution for the ash treatment and disposal. The ash was burned in an atmospheric circulating fluidised bed (CFB) pilot plant in Karhula, Finland. In the tests, the main objective was to decrease the ash carbon and PAH contents to an environmentally acceptable level. The target for the fly ash composition was to minimise the formation of dioxins and furans in the combustion.

Filter ash from the gasification tests was fired in a 1 MW_{th} CFB-pilot plant, as shown in Figure 4.8. The ash was fed with a screw feeder into the CFB furnace.

The process data measurements (temperatures, pressures, etc.) were carried out by the Alcont process control system. The measured data from the Alcont was also transferred automatically to a PC (personal computer) during the test runs.

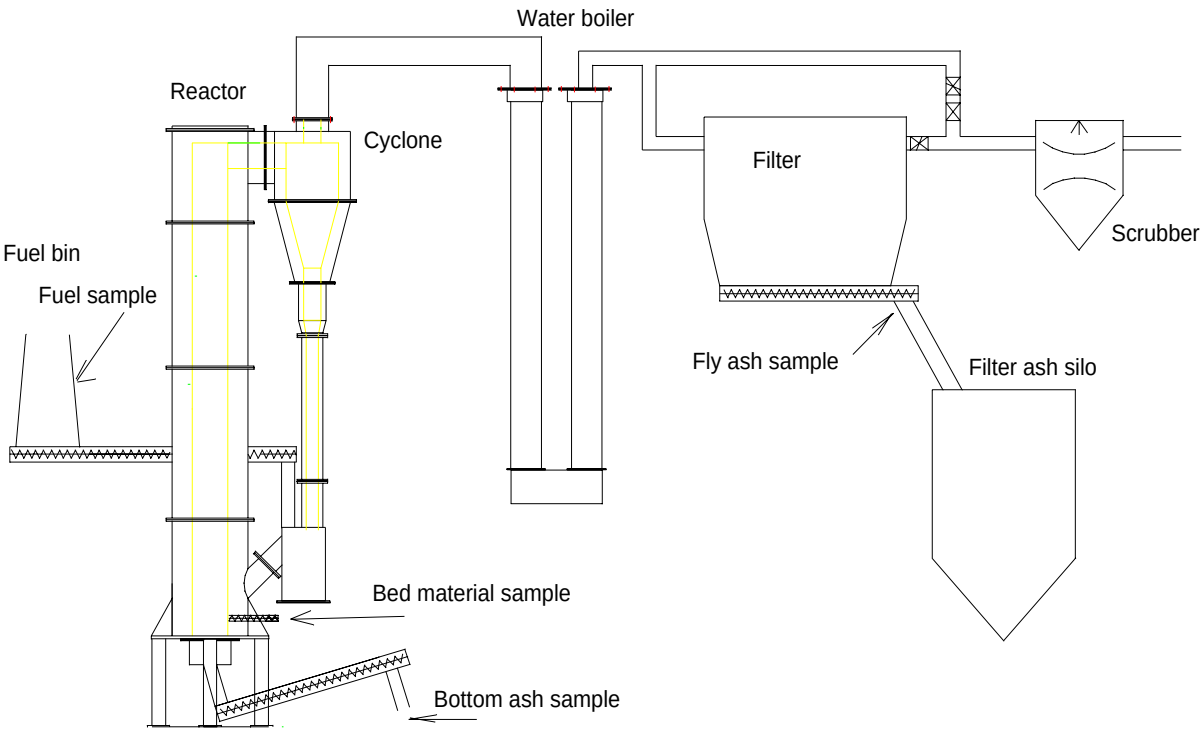


Figure 4.8 The general process layout and the sampling points of the pilot plant

The oxygen contents in the furnace and flue gas, as well as CO, CO_2, SO_2, NO_x, N_2O and HCl emissions were analysed with continuously operated analysers.

The combustion of the gasifier filter ash was carried out at low temperature, i.e. below the KCl melting point 776 °C, to avoid bed agglomeration. Therefore, high excess air was used for temperature control. Due to the considerable changes in ash quality and its carbon content, 20-40%, the combustion was somewhat fluctuating, but still under control.

Flue gas O2 (dry)	%	8.8 - 12.4
Furnace air coefficient	-	1.6 - 2.2
Flue gas CO_2 (dry)	%	8.0 – 11.1
Combustion efficiency	%	91 – 93
CO emission (6% O_2, dry)	ppm	3000 – 5500
NOx emission (6% O_2, dry)	ppm	408 - 550
N2O emission (6% O_2, dry)	ppm	0
SO2 emission (6% O_2, dry)	ppm	0 – 15
HCl emission (6% O_2, dry)	ppm	0 – 6
HCl retention	%	99.7 - 100

Table 4.10 Emissions from gasifier filter ash combustion

The CO emission was high and fluctuating. No doubt, this was caused by low combustion temperature and variations in the gasifier filter ash quality and composition.

Sulphur dioxide and HCl were almost quantitatively captured by the alkali ash components. NO_x emission was surprisingly high, 408 – 550 ppm. The obvious reasons are the high excess air and high alkalinity of the ash.

The unburned carbon contents were 0.1 – 0.5% in the bottom ash and 2.5 –3.5% in the filter ash after combustion.

The concentrations of the toxic components in the gasifier filter ash were reported in chapter 4.4.9. The same components were analysed also from the ashes of combustion, see Table 4.11.

	Bottom ash	Filter ash
Components	**ng/g**	**ng/g**
Chlorophenols	Not detected	Not detected
Chlorobenzenes	0 - 1	2 – 5
PCB	Not detected	Not detected
PAH	< 0.009 mg/kg	0.81 – 1.09 mg/kg
		pg/g
PCDD (total)	0	76 –95
PCDD (I-TEQ)	0	0
PCDF (total)	0-1	44 – 86
PCDF (I-TEQ)	0	1

Table 4.11 Toxic organic components in the ashes from combustion

As a conclusion, the combustion efficiencies achieved were sufficiently good, 91-93%. Due to a strict and low temperature limit, CO emissions were high. Content of combustible carbon in the fly ash varied between 2.5 and 3.5 w-%, which allows recycling back to the Danish fields. In bottom ash carbon content was insignificant.

Even better conversion for PAH than for carbon was achieved. The carbon conversion was around 90% and the decomposition rate for PAH about 99% in all test runs. The PAH concentrations in the filter ash were about 1 mg/kg, that is on acceptable level (<3 mg/kg) according to Danish legislation.

Sulphur and chlorine were captured almost quantitatively in the filter ash. On the contrary, emissions of NO_x were high, 400-560 ppm, dry, 6% O_2. The obvious reasons for the high NO_x emissions were high excess air and high alkalinity of the bed material.

It can also be concluded, that only very low levels (I-TEQ 1 pg/g in bag house filter ash) of dioxin and furans are formed in the combustion of fly ash.

5. DESIGN STUDY

5.1 Introduction

The Design Study covers a comprehensive description of a full-scale straw based CFBG. Such a gasification plant could contribute to fulfilling the Danish National plan for the use of biomass. The selected size is 100 MW_{th}, which corresponds to an annual straw consumption of 150,000 tonnes.

The basis for this work is the positive results from the process validation phase, and also the theoretical and practical know-how of the partners regarding biomass in general and straw in particular, circulating fluid beds, gasification and large power plant processes. In order to be able to scale-up all equipment and machinery the main processes have been modelled and evaluated, solutions for safe operation have been developed and typical and possible operational situations determined.

The description of the Design Study is the final result of evaluating several technical solutions, which have been investigated during the project. The aims of the work is to present a 100 MWth straw based CFBG connected to a power plant boiler, the required equipment and finally calculate a budget price and the overall project economy.

5.2 Main process diagram

The main process diagram is also shown in appendix 9.5.

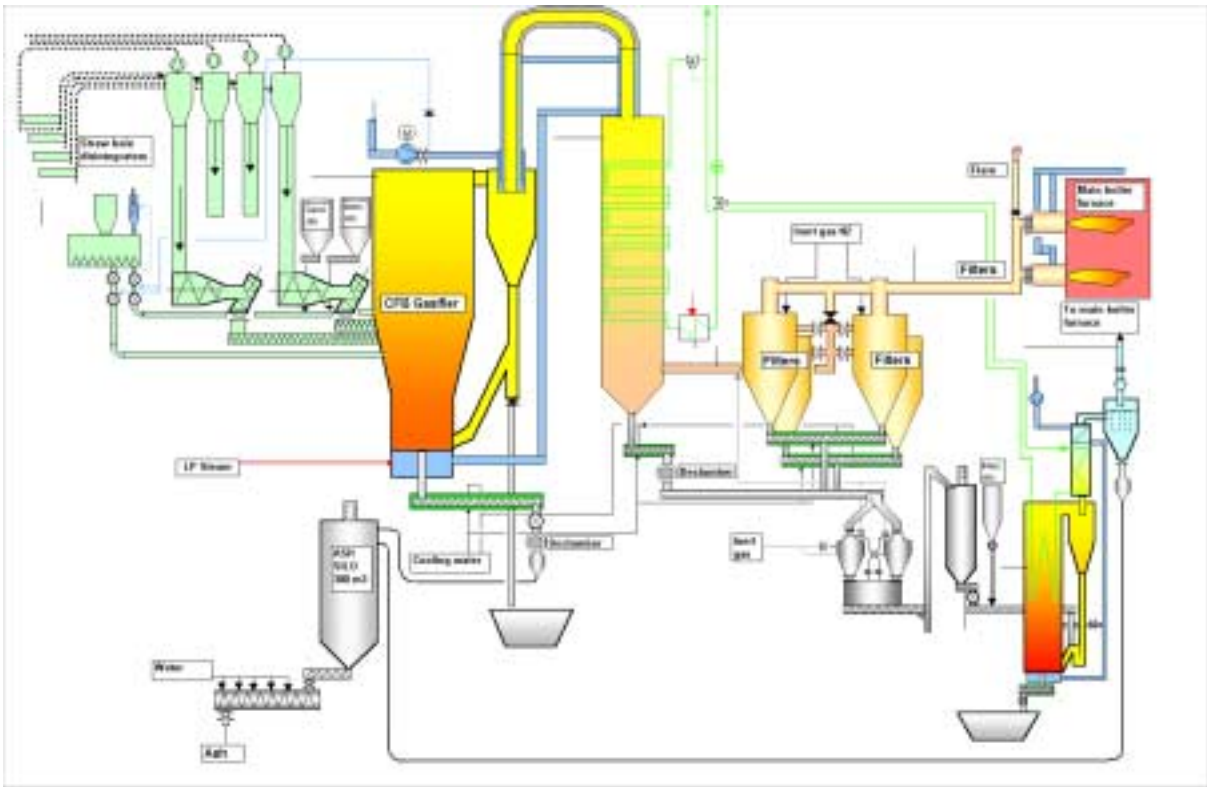


Figure 5.1 Main process diagram

5.3 Gasification system

5.3.1 General description

Shredded straw and wood chip type biomass will be gasified in a Circulating Fluidised Bed gasifier to combustible gases. To get the circulating fluidised bed, limestone and sand is added in the gasifier. This is the circulating fluidised bed (CFB) principle on which the gasifier operates. Typical superficial velocities are 4-5 m/s. Typically straw gasification takes place at about 800 - 840 °C and wood gasification at 850 – 880 °C bed temperature.

As gasification medium air and steam is blown into the gasifier. The gasification takes place in the near atmospheric pressure around 1.075 bar (a) and in the temperature 800 - 840 °C (wood 850 –880 °C). The pressure in the gasification plant is kept over the atmospheric pressure. The lowest pressure is in the gas duct in the burners. The heat value of this gas is rather low compared with natural gas. A typical lower heat value of this gas is 5.0 – 5.2 MJ/kg (straw). This gas is called Low Heat Value gas (LHV -gas).

The hot gas from the gasifier will be first cooled in the airpreheater to 750 °C.

5.4.2 Design and process values

The gasifier is designed to convert 7 kg/s straw to combustible LHV gas. Maximum gas flow is 16 kg/s and maximum airflow is 9.0 kg/s.

The air and gas velocity in the grid is 4.3 m/s and in the freeboard 4.2 m/s. The design operation temperature in the gasifier is 810 °C. The operation temperature can be chosen according to the fuel quality.

The diameter of the bed is 2700 mm and the freeboard diameter is 3940 mm. The height of the reactor is 20 m. Refractory lining is 350 mm thick in the reactor and hot cyclone. The hot cyclone is inside 4000 mm in diameter and the Vortex finder is 1700 mm in inside diameter.

The gasifier consists from the inside refractory lined atmospheric vessels, where straw and wood chips are gasified in a circulating gas-solid particle suspension, which is a so called Circulating Fluidised Bed. The refractory lining is designed up to 900°C continuos operation temperature and maximum 1100 °C. The lining material is high alkali resistance material in the reducing atmosphere and for the shell temperature max 50 °C above the surrounding air temperature.

The hot LHV gas from the gasifier flows from the gasifier cyclone trough the air preheater.

The air temperature before the airpreheater is normally 40 °C. The maximum temperature is 80 °C. The air temperature after the airpreheater is 250 °C (max allowed 350 °C). Gas is cooled in the airpreheater to 740 °C. The airpreheater is inside 1700 mm and outside 1840 mm the total length of the airpreheater is 11.5 m.

5.3.3 System description

Fluidising is achieved by blowing air through the bed material lying on the grid (air distributor). Fluidising beds can be divided into four categories. The type of fluidising bed is dependent on the air velocity in the bed. As the velocity is increased the bed changes from fixed, through bubbling and turbulent, to circulating.

Bubbling beds operate at superficial velocities less than 2 - 3 m/s. There is a distinct visible bed level.

Above this minimum velocity the bed expands more and particles become entrained in the flue gas and are carried out of the bed. There is no longer a distinct visible bed level, but the bed become less and less dense through to the combustion chamber. The coarser entrained particles are separated in a hot cyclone and returned back to the bed.

The gasifier consist of three internally refractory lined parts:

- The reactor where the gasification takes place
- The cyclone to separate bed material from the gas
- Return pipe for circulating bed material

The gasification air is fed to the bottom of the reactor via air nozzles. The fuel is fed in the lower part of the gasifier. The gasification air has a pressure about 1.26 bar (a), when it enters into the reactor. The temperature of the air is about 250 °C.

The reactor part is connected to the cyclone, which separates the circulating bed material from gases. The gas goes out from the cyclone to the airpreheater. The separated solids are led back to the reactor via the return pipe.

When gasification air enter under the solid bed, the gas velocity is so high, that the particles start to be fluidised. In this stage the bed expand and all particles are in rapid movement. The fluidising bed looks like a boiling liquid. The gas speed is so high, that part of the particles are flowing out from the reactor. The reactor contains lot of particles moving rapidly up and down. In this stage the reactor has excellent heat and material transfer properties. The temperature in this fluidising bed is 800-830 °C. The incoming straw contains about 14% water, 82% combustibles and 4% ash. The straw enters the gasifier in the level where the upward flowing gas does not contain any free oxygen. In this hot bed straw particles start to dry rapidly and also the volatiles in the straw start to release in the gases. When the bed does not contain any free oxygen the combustible pyrolysis product (gas) can not be oxidised. In this stage also CO_2 and H_2O react with charcoal. The charcoal will be mixed with bed material and when charcoal goes to the bottom of the bed it will oxidised to CO and CO_2. The circulating bed material coming from the cyclone contains also fine charcoal. This will be oxidised, when it comes to the bottom of the reactor. The circulating bed material serves as heat carrier and so it balances the temperatures in the process.

The straw feed will be 7.0 kg/s (10 - 20 % moisture) and airflow 8.0 – 9.0 kg/s.

The hot gas flows from the cyclone directly to the airpreheater and the gas cooling, which is located nearby the cyclone.

The airpreheater is constructed of two ducts. The gas flows in the inner duct and air is flowing in the jacket between the ducts. The inner duct is made from fireproof steel and the outer duct from stainless steel. The air preheater is operating according the co-current principle.

The air preheater is divided in two parts. The first part is at the same time the Vortex finder in the hot cyclone. The gas flows in the first part upward. There is a refractory lined connection duct between the airpreheater parts. The connection duct is a 180-deg° elbow. The refractory lining is also an abrasion proof construction allowing relatively high velocity in dusty gas. After the elbow there is an ejector constructed in the duct mixing the dust evenly in the gas stream before the last air preheater. This connection duct is supported on the steel construction. The steel bellows in the airpreheater are compensating the heat expansions and the possible vibrations in the gas cooler below the last airpreheater. In the last airpreheater gas and air flows downward.

When the Vortex finder in the hot cyclone is a part of the airpreheater and the refractories in the cyclone stay hot for a long time, there are ventilation valves in the air ducts to lead cooling air in and out to Vortex finder after the stop of the plant.

When the gasification plant is shut down for long time, the gasification system including gasifier, gas cooler and filter are conserved in the N_2 atmosphere to avoid the condensations and corrosion. The valves are closed. Bed material and ashes are taken out from the gasifier, gas cooler and silos.

The gasifier is standing on the concrete foundations and the center line of the gasifier reactor is the fix line for the gasifier construction. The gasifier cyclone is supported on the reactor shell and it will move 3 mm, when the plant is heated up. The heat expansions in both will take place freely upwards.

The gasifier, cyclone and return pipe are refractory inside lined steel vessels. The refractories are inside anchored in the steel shells and equipped with gas barriers. The refractory lining is constructed in tree layers. The refractories are low iron material. The max Fe_2O_3 content is 1 %. The shell under the refractories will be protected against corrosion with special painting. The weight of the refractories is around 300 ton.

The gasification air is brought to the grid via the wind box. The grid consists of a fireproof steel plate containing many closely pitched nozzles. The purpose of the nozzles is to fluidise the bed material evenly and also prevent the back flow of material. This requires a minimum pressure drop and hence a minimum air flow. The space between the top of the air nozzles and steel plate is refractory lined.

The bed material feed capacity is adjusted according to the fuel feed. The bed material feed system will depressurise after the operation as well the other parts in the plant.
The gasification air is taken from the atmosphere by the fan. It first passes through the airpreheater before it is being brought to the wind box where it is blown through the grid to fluidise the bed and provide gasification air. The steam for the gasification is blown in the air wind box.

The fan is equipped with inlet silencer. The design of the fan is max 10.0 kg/s and a maximum pressure increase of 0.30 bar.

The gasification air fan control is e.g. via fan outlet valve control according to the required air flow, which is measured by the Venturi in the outlet duct.

5.4 Gas cooler system

5.4.1 General description

The hot gas from the gasifier will first be cooled in the airpreheater to 750 °C. After that there is a gas cooler, where the heat is transferred to the feed water from the main boiler. After cooling the LCV gas will be filtrated and led to the gas burners in the main boiler. The main boiler is a once through type steam boiler.

The heat from the char/ash combustion will be recovered to the same water too.

5.4.2 Design and process values

The hot LHV gas from the gasifier flows from the gasifier cyclone, through the air preheater and further to the waste heat boiler.

The gas cooling system is a water tube type waste heat boiler. The heat from the boiler is used for preheating of the feed water from the main boiler. The inlet water temperature is designed to be 175°C and outlet temperature 275 °C. Heat from the flyash incineration will be recovered to this water cycle too.

To able to control the inlet water temperature, there is a water preheater before the gas cooler. This is only needed, when the main boiler is in the low-load operation. Also there is a separate small feedwater pump to ensure the water flow through the cooler, when the main Boiler is in the low-load operation.

The gas cooler will cool the gas down to 350 °C. The recovered heat is 9024 kJ/s in the gas cooler and 2632 kJ/s in the flyash incinerator.

The feed water system is shown on the main process diagram in appendix 9.5.

5.4.3 System description

The hot gas flows from the airpreheater to the gas cooler, which is located nearby the cyclone. The gas flows in the cooler downward. The gas cooler is equipped with the spring hammer type soot blowers.

The gas cooler is a single pass water tube construction. The inlet chamber for incoming gases is about 4 m high and 2 x 3 m wide. There are 7 horizontal tube bundles inside. The tube size is 38 mm in diameter. There is 600-mm high free space between each bundle for maintenance. The walls are water-cooled gas tight welded membrane construction. The bottom cone of the cooler is a steel plate construction. The height of the cooler is about 25 m.

To ensure the water flow through the cooler also in case, when the main boiler is low load operation, there is a separate small feedwater pump. This will be in operation only, when the main boiler is in operation with 40 – 50 % loads.

To be able to control the gas temperature after the gas cooler, there is a preheater for water before the gas cooler.

The flyash incinerator has a back pass, which is water cooled with the same water. This is a similar construction as the gas cooler. The inlet chamber for incoming gases is about 1 m high and 0.8 x 1 m wide. There are 8 horizontal tube bundles inside. The tube size is 38 mm in diameter. There is 600 mm high free space between each bundle for maintenance. The walls are water-cooled gas tight welded membrane construction. The bottom cone of the cooler is a steel plate construction. The height of the cooler is about 15 m.

The walls of the flyash incinerator furnace are water-cooled gas tight welded membrane construction.

When the gasification plant is shut down for a long time, the gas cooler is conserved in a N_2 atmosphere to avoid the condensations and corrosion. The valves are closed.

5.5 Product gas system

5.5.1 General description

The cooled produced gas will be cleaned in 4 bag house filters. The filters will separate most of the particles from the gas. The cleaned gas is suitable to burn in the pulverised coal fired

boiler. The cleaned gas will be burned in 4 gas burners in the main boiler. The principle of the product gas system is shown on the main process diagram in appendix 9.5.

5.5.2 Design and process values

The filters and burners are designed for the following condition:

Gas flow (total)	Nm^3/s	14.0
Gas temperature	°C	350 (for process performance)
Gas temperature	°C	450 (for equipment construction)
Gas pressure	bara	1.015 (for process performance)
Gas pressure	bara	1.1 (for equipment construction)
Dust content before	g/Nm^3	50
Dust content after	mg/Nm^3	100

5.5.3 System description

The filter system consists from 4 similar filter units. The filter vessels are round with conical bottoms. The gas volume of the filters is about 780 m^3.

The material in the filter vessels is carbon steel, except the bottom cone that is made of stainless steel. The filter bag material is FB900 from 3M.

The filters are equipped with steam tracings to avoid tar condensation particularly in the start up. The steam for tracing is 40 bar. The filters are heat insulated. The steam tracing pipes are between the shell and heat insulation.

The filters are equipped with pulse gas and sonic horn cleaning systems. Nitrogen is used as pulse gas. The estimated pulse gas consumption is about 250 kg/h. The pressure of the pulse gas should be over 4 bar(a).

The inlet openings into the filters are equipped with butterfly type valves. The size of the valves is DN 800. The valves are metal seated. In the gas duct is also a bypass valve for the filters. The size of the bypass valve is DN 1200.

The filters are equipped with explosion doors type rupture disks. The rupture disks are placed on roof of the filters. The opening pressure of the rupture disks will be 1.1 bar(a). In the case of ruptures of the disks gas will be blown up over the gasification building.

The gas duct from the filters to the burners is equipped with steam tracing and the ducts are heat insulated. The material in the ducts is carbon steel.

The gas burners are equipped with separate gas flow and airflow measurements to able to control the gas combustion in each burner. The combustion air for the gas burners is taken from the main boiler air system.

The gas burners are equipped with the double shut off valves (DN 800) and ventilation valve (DN 50). Each burner is equipped with ignition burners and flame scanners.

To be able to ventilate the gasification system from combustible gases, there is also a flare to burn the gases in the case, when the main boiler is not in operation. When the main boiler is in operation the gases will be purged into the main boiler. The flare is utilised only when the main boiler is not in operation. The capacity of the flare is max 7 kg/s gas.

5.6 Straw feed system

5.6.1 General description

Straw from the bale disintegrator will be fed with the screw conveyor to the pneumatic transport system. In this system straw first enters the windscreen, where the stones and other larger heavy particle are separated. This windscreen is a so called Zigzag screen, where heavy particles are falling down. The heavy particles will fall down in a closed container.

The circulating air from the pneumatic transport system will be divided in the two streams in the windscreen. The air velocity in the windscreen can be controlled with this air split and so also the size of the separated particles.

The screw conveyor transports loose straw in the windscreen. The supplementary air for the pneumatic transport system enters also via this screw. This will minimise the dust problems in the straw feed. In the pneumatic transport system is a small under pressure.

Straw will be transported pneumatically to the cyclone, where straw will separate from the air. Straw falls down to the feed chute over the plug screw. Air from the cyclone will come back to the windscreen via a fan. Part of the air from the cyclone will be extracted to the small bag house filter. There will be a separate fan to blow the air from the filter out to atmosphere. The dust from the filter will be transported to the feed chute over the plug screw.

The plug screw and the plug chopper are described in Chapter 4.2.3 and 4.2.4.

Straw from the plug chopper will fall down to the feed-in screw, which feed straw into the gasifier. The feed-in screw is water-cooled.

There are 4 similar straw feeding systems. The principles in one of the straw feed systems are shown in figure 5.2. Parts of the straw feed system are also shown in the main process diagram in appendix 9.5.

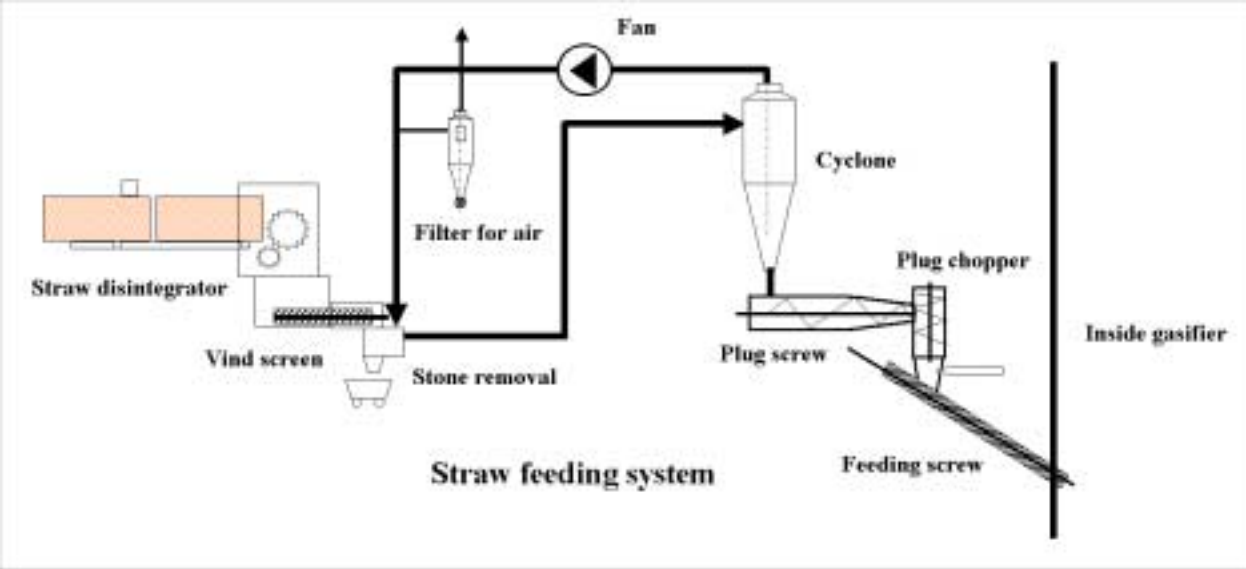


Figure 5.2 Straw feed system

5.6.2 Design and process values

The straw feed system is designed for the following condition:

Pneumatic transport

Number of feed lines		4
Capacity/line	m³/h	300
Minimum capacity/ line	m³/h	12
Straw density	kg/m³	30
Capacity of one line	kg/s	2.5
Duct size	m	0.500
Air flow	kg/s	7.00
Air temperature	°C	15
Air pressure	bara	1.000
Air moisture kg H_2O/ kg d.a.	kg/kg	0.005
Length of transport ducts (average)	m	40
Air density	kg/m³	1.205
Air flow	m³/s	5.809
Duct size	m	0.500
Air velocity	m/s	29.58

Wind screen

Flow area	m²	0.4
Flow area B	m	1.000
Flow area L	m	0.400
Air velocity (max)	m/s	14.52

Cyclone

Diam. of Vortex finder	m	0.800
Diam. of cyclone	m	2.000
Height of cyclone barrel	m	2.800
Height of cyclone cone	m	4.500
Height of cyclone	m	7.300
Inlet opening A	m	0.900
Inlet opening B	m	0.400
Inlet velocity	m/s	16.14
Outlet velocity	m/s	11.56

Pressure drop	Pa	1324

Filter

Air to filter	kg/s	0.5
Filter face velocity	m/s	0.02
Filter area	m²	20.75

Fan

Air flow	kg/s	6.5
Pressure increase	kPa	5.7
Motor	kW	110
Power consumption	kW	73

Feed chute

Height	m	8.500
L	m	1.200
B	m	0.650
Volume	m³	6.6

The plug screw and the plug loosener descriptions are presented in Chapter 4.2. There is also a tight damper to close the connection to the feed-in screw. The connection to the feed-in screw is 800 x 800 mm. The feed-in screws are water-cooled.

Feed-in screw

Inclined	deg°	30
Diameter	m	0.800
Length	m	2.300
Speed	rpm	50
Capacity	m³/h	603
Motor	kW	22

5.6.3 System description

The straw bales from the storage are transported on four feed lines to the bale disintegrator. The transport velocity will define the straw feed capacity into the gasifier and so also the capacity of the gasification plant. The straw feed systems after the bale disintegrators only consists of the direct feed lines to the gasifier. There is no storage volume in those lines.

The feed capacity of each line is 300 m³/h. Full capacity can be reached with tree feed lines. The minimum feed capacity should be 12 m³/h.

The feed time from the bale disintegrators to the gasifier is about 30 sec.

The transport screw from the bale disintegrator feeds straw into the windscreen. The shaft of the screw goes through the windscreen. So the outlet end of the screw is part of the windscreen. The air circulation in the windscreen will be chosen in the commissioning phase and will be kept constant afterwards. Stones over 5 - 15 mm will be separated in the windscreen. This windscreen is a so called Zigzag windscreen, where the straw is transported pneumatically upwards in the duct, which is formed from several straight pieces connected to each other. The straight duct pieces form 15 degrees angle from the vertical line to side. Inside the duct angles the straw hit against the walls and heavy particles are separated. The heavy particles fall down to the bottom container and light straw fly upwards to the pneumatic transport system. See figure 5.2.

The pneumatic feed line is about 40 m long. There is a cyclone, which separates straw from the air. Air will be circulated back via a high-pressure fan. Part of the air will be blown via a filter out of the system. This will prevent dust to accumulate in the pneumatic feed line. The new air to replace the extracted air will come in with the straw. This means, that there is a small vacuum in the pneumatic feed line. This will minimise the dust problems in the straw transport system.

The feed chutes under the cyclones serve as balancing volume for small variation in the straw transport. This volume is also enough to collect straw out from the transport line.

The cyclones are equipped with CO-detectors and sprinkler system for fires.

The plug screw, plug chopper and straw damper are described in other system descriptions. The straw dampers are so tight, that the plug screw and plug choppers can be changed during the operation of the gasifier. This is necessary, because the wear in the plug screw and plug chopper may require the sharpening of the screws once in 3 – 5 weeks.

The four feed-in screws push straw into the gasifier. Those screws are only supported in one end. The screws are inclined downwards 30 degrees. The diameter of the screws is 800 mm. The end of the shell and shaft are water-cooled.

5.7 Straw storage, conveying and preparation facilities

5.7.1 General description

The handling and storage facilities for the straw bales consist e.g. of a storage building with a capacity corresponding to 48 hours of full load operation. The bales are transported from the farmers by trucks. Inside this storage building the trucks are unloaded and the bales are either stored or distributed to the conveying system.

The conveying system transports the bales to the four disintegrators situated in the connection to the fuel feedline of the gasifier.

The storage building is divided into two parts each having a crane and a track for unloading the trucks. The design is dedicated the use of Hesston bales transported on trucks in two layers with 12 bales on the truck and 12 bales on the trailer.

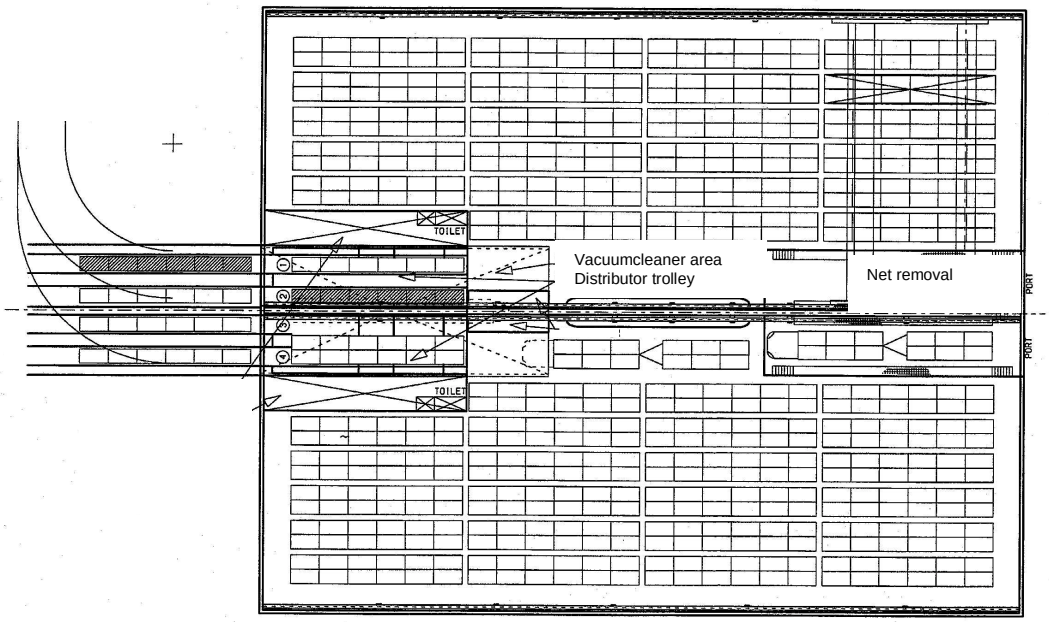


Figure 5.3 Ground plan of straw storage

5.7.2 Unloading of trucks

Inside the storage building unloading of the trucks are divided into three stages in separate areas of the unloading zone.

First stage starts just inside the gate, where the truck stops parallel to a catwalk making it possible for the truck driver to remove the net covering the load. Big vertical bars are protecting the truck driver against bales tilting from the storage area. When the net is removed and packed and the next area is free from the previous truck, the present truck can continue to the next stage.

Second stage includes an area covered by the crane. The cockpit of the truck is protected from falling bales by a platform supporting the distribution system for the feedlines. The crane empties the truck with two lifts each including 12 bales. During the lifting the mass and water content of the bales are measured automatically. In case the water content exceeds the maximal allowable in one or more of the bales, all of the bales are rejected.

When the crane is operating in the unloading zone, it is manually operated. When the bales are picked up, the crane will be operated by the storage management system that moves the bales either to the storage area or directly to the distribution system. When the truck is empty and the next area is free, the truck can continue to the third stage.

Third stage involves cleaning of the truck before leaving the storage building. The truck stops parallel to a catwalk making it possible for the truck driver to operate a vacuum cleaner. After this the truck leaves the storage building.

5.7.3 Storage

The storage has a capacity corresponding to 48 hours of full load operation. This is based on following unloading time schedule given by noise emission conditions:

Monday – Friday	7 AM - 10 PM
Saturday	7 AM - 2 PM
Sunday	No unloading

Monday morning 7 AM the storage still contains bales for about 8 hours of operation, which insures continuous operation of the boiler in case of interruptions in the unloading system e.g. during rush hours.

The storage building is divided into two parts each having a crane. This insures full redundancy in case of break down. The bales are stacked in up to five layers.

5.7.4 Distribution system

The distribution system moves the bales to the four conveying lines leading to the disintegrators. The distribution system is based on a trolley that receives twelve bales from the crane in a six by two matrix. The trolley is covering both parts of the storage building. The trolley feeds each line with six bales at a time. When the trolley is empty, the storage management system is requested to deliver twelve more bales using one of the cranes. To insure high availability a spare trolley is positioned at the track. The spare trolley automatically takes over in case of problems with the first one.

5.7.5 Conveying system

The conveying system consists of four conveying lines leading to the disintegrators. The conveying lines are based on modular constructed chain conveyers starting at the distribution system and ending in front of the disintegrators. The maximal acceptable slope is approx. 15 °. The last sections of the conveying system are controlling the feeding rate to the disintegrators.

5.7.6 Disintegrators

The disintegrators are cutting the strings and are reducing the straw density from 130 kg/m³ to 30 kg/m³. The capacity of the disintegrators and connected systems are about 16 bales per hour. It is then possible to operate the gasifier at full load with three of four lines in operation.

5.8 Wood fuel feed system

5.8.1 General description

Wood chips and similar wood based material can be used as fuel in the gasifier. The lorries will transport the ready chipped wood to the site. There is a receiving station for the wood chips. The receiving station is a live bottom bunker. The conveyor under the bunker lifts wood chips to storage silo, which is a round covered silo, where a turning screw will discharge wood chips to the pneumatic transport feed line. When this gasification plant is designed to use straw and wood and there is 4 feed lines for straw and 2 for wood, the pneumatic transport system is chosen to save space for all fuel feed systems. There is a divert damper in the pneumatic feed line to divide wood chips to two feed bins. The feed bins will meter wood chips into the gasifier via two rotary feeders, which are pressurised to a

higher pressure than the gas pressure in the gasifier. Air from the main gasification air fan is used as sealing air. The wood fuel system is included in the main process diagram shown in appendix 9.5.

5.8.2 Design and process values

The wood chip feed system is designed for the following condition:

- Receiving station volume m³ 100
- Live bottom feed capacity m³/h 400
- Storage silo capacity m³ 2000
- Pneumatic feed capacity m³/h 120
- Feed bin volume m³ 2 x 20
- Feed capacity from the bins m³/h 2 x 60

5.8.3 System description

In one wood chip lorry with the trailer can transport maximum 80 m³ wood chips. So the receiving capacity 100 m³ should be enough. The live bottom of the receiving station is a double stoker type. The stokers are hydraulic driven. The receiving bunker is an underground concrete construction.

The drag conveyor lifts wood chips from the receiving station to the storage silo.

The moisture content in the wood is normally much higher than in straw. This means that the gasifier capacity with variable moisture in wood is (wood only):

Wood moisture %	Gasifier fuel capacity MJ/s	Chemical heat to the main boiler MJ/s	Heat to the main boiler feed water MJ/s	Sensible heat to the main boiler MJ/s
50	50	28	12	7
40	61	39	12	7
30	72	51	12	7

The wood storage 2000 m³ is as energy about 5.6 TJ, when the moisture in the wood is 50%. So this storage capacity is enough for 31 hours operation with 50 MJ/s capacity.

The chip storage is a round silo with a diameter of about 18 m. The walls are about 8 m high and there is a conical roof over the silo. The total height of the silo is about 18 m. The silo is equipped with CO-detectors and sprinkler system for fires.

In the silo is a turning screw discharger, which transport wood chips in the centre of the silo. Wood chips falls down from the centre to the pneumatic feed line. There is a rotary feeder in the inlet to the pneumatic feed line.

The pneumatic feed line is designed for wood chips with a maximum size of 50 mm. The pneumatic feed line size is DN 150. The conveying airflow is 0.9 kg/s and pressure max 0.5 bar. There is a divert damper in the feed line to divide the fuel flow to two feed bins. The cyclones separate wood chips from the conveying air. The size of the cyclones is 600 mm in diameter and 2 m in height.

The volume of the feed bins is 20 m³ each and the double screw dischargers in the bottom are able to feed 60 m³/h wood chips into the gasifier. There are two rotary feeders in the feed chute to the gasifier. There is sealing air purge between the rotary feeders to create higher pressure there than in the gasifier. The escape air from the rotary feeders will be collected to the filters located over the feed bins.

The wood feed system is a secondary fuel system and the gasification plant can be operating simultaneously with wood and straw as fuel. In the case when wood and straw is used as fuel, the wood feed will be kept constant and the gasifier capacity will be controlled with straw feed.

5.9 Bed material system

5.9.1 General description

Shredded straw and wood chip type biomass will be gasified in a Circulating Fluidised Bed gasifier to combustible gases. The bed material (fine limestone and sand) is a heat carrier, which ensure the uniform temperature distribution in the gasifier.

Same limestone as in the gasifier will be used also in the fly ash incinerator as bed material. The bed material system is shown on the main process diagram in appendix 9.5.

5.9.2 Design and process values

In the normal operation sand and limestone is fed continuously into the gasifier. There is storage silos for sand and limestone. The sand silo capacity is 50 m³ and limestone silo capacity is 100 m³. This is enough for 5 – 10 days' of operation.

The bed material feed will be proportional to the fuel feed. The sand feed is 25 – 40 % and limestone feed is 75 – 60 % from the total bed material feed. The feed bins are designed to be in size 5.5 m³.

The grain size of the bed materials is (D50) in sand 250 – 350 microns and in limestone 450 – 550 microns. Bed material should be dry.

5.9.3 System description

Straw and biomass contains alkalies, which are lowering the ash fusion temperature. Especially alkalies are reacting with silicates. The alkali-silica compounds are sticky in the temperatures 750 – 950 °C and the bed material particles like sand are bonded together and fluidisation is not possible after this reaction. This means, that if only sand is used as bed material, the gasification temperature is very much limited due the alkali-reactions with silica.

Bed material is continuously added into the gasifier and into the fly ash incinerator to prevent the build-up of the alkalies in the fluidised beds. If the bed material amount will increase in the fluidised bed, the bottom ash discharge screw will feed bed material out from the gasifier and incinerator. The gas pressure drop over the bottom part of the gasifier and incinerator will indicate the bed material amount in the fluidised bed. So a part of the alkalies is escaping from the gasifier with the bottom ash.

The operation temperature of the gasifier is 800- 820 °C. This means, that the limestone will be calcined slowly ($CaCO_3$ ->CaO + CO_2). In this reaction limestone will break down to dust, which will fly away from the hot cyclone to the fly ash filter. CaO in the gasifier will act as the catalyst in the tar cracking process. CaO-particles are also transporting alkali out from the gasifier.

The combustion temperature in the incinerator is so low, that calcination of the limestone does not take place. So the bed in the incinerator is mainly limestone particles.

Limestone and sand will be transported to the site in lorries, which can blow the bed materials pneumatically into the silos. The bed material storage silos are equipped with filling pipes. There is an exhaust air filter on the top of the silo. On top of the silos are also safety valves to release the pneumatic transport air out from the silos in case of filter blockage.

The silos are steel leg supported cylinders with bottom cones. The bottom cones are equipped with electric heat tracing and insulation to avoid water condensation.

In the bottom cones will be installed fluidisation air nozzles to ensure free flowing of the bed materials.

The outlet connections from the silos are equipped with manual gate valves, rotary air lock feeders and dome type valves with actuators. The rotary air lock feeders are metering the bed material flow out. The dome valves have an expanding rubber seal ring, which makes the valves airtight even with worn domes. The expanding of the seal ring will be done with pressure air.

Limestone Silo:

		Process value	Design value
Volume	m³	100	100
Diam.	m	3.500	3.500
Cylinder height	m	8.000	8.000
Cone height	m	3.983	3.983
Cone angle	deg°	22.5	22.5

Sand Silo:

		Process value	Design value
Volume	m³	50	50
Diam.	m	2.600	2.600
Cylinder height	m	8.000	8.000
Cone height	m	2.897	2.897
Cone angle	deg°	22.5	22.5

Limestone rotary feeder to the sender vessel:

		Process value	Design value
Limestone feed capacity	kg/s	2.210	2.210
Limestone feed capacity	m³/h	8.0	8.0
Limestone density	kg/m³	1000	1000
Limestone temperature	°C	25	25
Rotor diameter	m	0.250	0.250
Rotor shaft diameter	m	0.150	0.150
Width of the rotor	m	0.200	0.200
Filling rate	%	84 %	84 %
Rotation speed	rpm	25	25

Sand rotary feeder to the sender vessel:

		Process value	Design value
Sand feed capacity	kg/s	2.650	2.650
Sand feed capacity	m³/h	8.0	8.0
Sand density	kg/m³	1200	1200

Sand temperature	°C	25	25
Rotor diameter	m	0.250	0.250
Rotor shaft diameter	m	0.150	0.150
Width of the rotor	m	0.200	0.200
Filling rate	%	84 %	84 %
Rotation speed	rpm	25	25

The sender vessels below the dome valves will be filled with bed material. When the vessel is full, the dome valve will be closed and sender vessel will be pressurised with pressure air. When the air pressure is increased to 3 – 4 bars, bed material starts to fluidise and will flow out from the sender vessel to the metering bins. The transport pipe is DN 80 and elbows are equipped with erosion proof linings.

The sender vessels are 0.08 m³ each in volume. The pressure air consumption for the transport is about 0.006 kg air / kg bed material. The sequence time is about 70 seconds.

There is a divert damper in the limestone transport pipe to divide limestone to the gasifier and incinerator.

The metering bins are 5.5 m³ in volume each. There are manual gate valves in the outlet connections. There are in the feed bins to the gasifier two rotary feeders and only one rotary feeder to the incinerator. The rotary feeders have variable rotation speed control. In the incinerator the pressure in the flue gas side is almost atmospheric, but in the gasifier the gas pressure is about 65 mbar in overpressure. There is sealing air purge between the rotary feeders into the gasifier to create higher pressure there than in the gasifier. The escape air from the rotary feeders will be collected to the filters located over the metering bins.

The bed material feed bins:

		Process value	Design value
Volume	m³	5.5	5.5
Diam.	m	1.500	1.500
Cylinder height	m	2.000	2.000
Cone height	m	1.570	1.570
Cone angle	deg°	22.5	22.5

Limestone metering rotary feeders for the gasifier:

		Process value	Design value
Limestone flow	kg/s	0.133	0.250
Limestone density	kg/m³	1000	1000
Limestone temperature	°C	25	25
Rotor diameter	m	0.250	0.250
Rotor shaft diameter	m	0.150	0.150
Width of the rotor	m	0.200	0.200
Fillingrate	%	85 %	85 %
Rotation speed	rpm	1.5	2.8

Sand metering rotary feeders for the gasifier:

		Process value	Design value
Sand flow	kg/s	0.066	0.120
Sand density	kg/m³	1200	1200
Sand temperature	°C	25	25
Rotor diameter	m	0.250	0.250
Rotor shaft diameter	m	0.150	0.150

Width of the rotor	m	0.200	0.200
Filling rate	%	42 %	41 %
Rotation speed	rpm	1.24	2.33

Limestone metering rotary feeder for the incinerator:

		Process value	Design value
Limestone flow	kg/s	0.025	0.050
Limestone density	kg/m³	1000	1000
Limestone temperature	°C	25	25
Rotor diameter	m	0.250	0.250
Rotor shaft diameter	m	0.150	0.150
Width of the rotor	m	0.200	0.200
Filling rate	%	85 %	85 %
Rotation speed	rpm	0.28	0.56

There are also gate valves after the rotary feeders to close the connection to the gasifier. This is needed to prevent air entering into the gasifier after stop of the gasification plant.

The bed materials to the gasifier fall into the feed chutes for the wood fuel. The bed material into the incinerator is fed in the ash transport screw to the loop seal.

5.10 Inert gas systems

5.10.1 General description

An inert gas system must be established to keep the product gasses inside the gasifier and the interior of the gasifier and the filter free of oxygen from the atmosphere. During operation, inert gas is used as a blocking gas in places where it is impossible to separate the reactor and the filter completely from the atmosphere – typically where straw and bed make-up are added and ashes removed. By creating a positive pressure using inert gas in these places, product gas is prevented from escaping into the atmosphere, since the pressure in the reactor is slightly positive in normal circumstances.

In connection with stops, inert gas must be fed into the reactor to displace the reactive and poisonous product gas. In the same process, inert gas is also fed into the filter as long as it remains hot because the large volume of free carbon will otherwise easily react with the oxygen of the air, thus causing severe damage to the filter bags.

Nitrogen is the inert gas chosen because it exists in the atmosphere and because it is easy and inexpensive to handle. Nitrogen up to 99,9 % of purity is generated at about 5.8 bars in a pressure swing adsorption (PSA) system.

A storage facility for about 1,000 Nm³ of nitrogen is established for peak loads and as back up should the nitrogen generator fail.

In connection with stops, large volumes of inert gas are needed to displace the product gas and prevent air from entering. Since both the reactor and the filter are hot, steam is used, which is available in large quantities in the main system. When the system has been cleaned, nitrogen is fed as the temperature – and thus the volume of steam – is reduced.

5.10.2 Design and process values

- Nitrogen generator capacity 300 Nm³/h
- Purity 99.9 %

• Air – nitrogen ratio	4.6	
Compressor		
• Output pressure	7	bars
• Capacity	2 x 700	Nm³/h
• Power consumption	2 x 75	kW
Storage facility		
• Medium-pressure storage facility, pressure	5.8	bars
• Medium-pressure storage facility, capacity	35	Nm³
• High-pressure storage facility, pressure	200	bars
• High-pressure storage facility, capacity	1000	Nm³
High-pressure compressor		
• Capacity	60	Nm³/h
• Power consumption	30	kW

5.10.3 System description

The PSA process is applied to generate nitrogen. It is a simple process, characterised by a relatively low consumption of compressed air at high concentrations of nitrogen (> 99%).

The PSA process consists of two adsorption towers filled with carbon molecular sieves. Compressed and purified air passes through the adsorption towers. Mainly oxygen is adsorbed on the carbon molecular sieve and nitrogen-enriched gas is leaving the tower. The oxygen concentration can be reduced to almost all required levels.

During adsorption in one tower, the second tower is totally regenerated – simply by depressurisation to ambient pressure. The oxygen-enriched off gas, with an oxygen content of 30-35 % by volume, is vented. After about one minute's adsorption in one adsorption tower, the process controller switches to the second tower, and the first one is regenerated.

The PSA system runs at a pressure of about 7 bars. Two compressors of 75 kW each provide the compressed air for the PSA system. When nitrogen is produced at a concentration of 99,9 %, the compressed air is to be generated at the ratio of 4,6 to 1 compared with the nitrogen.

A buffer of 35 Nm³ is established between the nitrogen generator and the process. The pressure in the facility matches the discharge pressure of the nitrogen generator.

A high-pressure storage facility containing 1,000 Nm³ of nitrogen is established for peak loads and as back up. 100 gas cylinders of 50 l each are connected, and the maximum pressure is 200 bars. Since it involves additional operating costs to compress the nitrogen to 200 bars, the operation of the system is optimised to minimise the use of the high-pressure storage facility.

5.10.4 Function analysis

Normal operation
Compressors, and thus the nitrogen generator system, aim at maintaining the pressure in the medium-pressure storage facility. By changing the revolutions of the compressors, the pressure can be kept constant.

If the pressure in the medium-pressure storage facility drops below the minimum, pressure is supplied from the high-pressure storage facility. When the consumption of nitrogen has

dropped to a level that the nitrogen generator is able to keep up, the pressure in the medium-pressure storage facility rises, thus making it possible to replenish the high-pressure storage facility.

Interruptions
If one compressor fails, the other's capacity will be sufficient to maintain normal operations. If the nitrogen generator or power fails, the process can use nitrogen from the high-pressure storage facility.

5.11 Ash incineration system

5.11.1 General description

The ash from the gas cooler bottom and ash from the product gas filters contain so much unburned carbon and other hydrocarbon elements, so that those ashes have to be incinerated before those can be utilised in the fields again.

Carbonious fly ash will be incinerated in a small Circulating Fluidised Bed boiler. The combustion temperature is kept in the CFB below the melting point of K_2CO_3 and KCl. The combustion temperature is max 750 °C. After this treatment the carbon content in the fly ash is below 5 %. Same limestone as in the gasifier is used as bed material in the incinerator too. The heat from the combustion is recovered for preheating of the main boiler feed water. The recovered heat is about 2.6 MJ/s. The ash incineration system is shown on the main process diagram in appendix 9.5.

5.11.2 Design and process values

The Incinerator is designed to burn 0.5 kg/s ash having a carbon content around 30 %. The incinerator is a small CFB boiler. In the CFB process the temperature control is very accurate, which is important, when this type of fuel is burned. The K-content in the ash is assumed to be up to 35 %. The max fluegas flow is 2.5 kg/s and airflow 2.0 kg/s. The combustion temperature is 750 °C.

The CFB furnace is rectangular and the bottom part is refractory lined. The upper part has water-cooled panel walls. The heat surface is about 25 m². In the bottom of the furnace is the air distribution grid. There is the outlet pipe with valve for bottom ash. The height of the furnace is 10 m. The Hot cyclone is inside 1600 mm in diameter and the Vortex finder is 500 mm in inside diameter. The return leg from the hot cyclone for the circulating material is refractory lined.

The ash to be incinerated will be fed in the loop seal below the return leg. Loop seal is fluidised with air. There is a small rotary piston compressor to supply air for the loop seal.

The temperature control in the furnace is made with water spraying. The cooling water is atomised with steam. The spray water is expected to be about 0.15 – 0 kg/s. When this direct water spray is used, the temperature control can be made with variable ash quality and also in the case, when there is fouling on the heat surfaces.

The back pass after the hot cyclone is first water cooled heat surfaces. There is a panel wall construction, where are also the cooling coils. The heat surface is about 130 m².

Below this is an air preheater to be able to cool flue gases down to 200 °C. Air will be preheated to 215 °C.

The flue gases will be cleaned in a bag house filter. The filter pulsing system is operating with pressure air.

The combustion air is divided to primary and secondary air. The flue gas from the filter is blown with the ID-fan to the main boiler furnace. The flue gas contains 200 – 2000 mg CO/Nm³ and some other unburned gases. This is the reason why the flue gas will be fed to the main boiler furnace.

5.11.3 System description

Fluidising is achieved by blowing air through the bed material lying on the grid (air distributor). Fluidising beds can be divided into four categories. The type of fluidising bed is dependent on the air velocity in the bed. As the velocity is increased the bed changes from fixed, through bubbling and turbulent, to circulating.

Bubbling beds operate at superficial velocities less than about 2 - 3 m/s and there is also a distinct visible bed level.

Above this minimum velocity the bed expands more and particles become entrained in the flue gas and are carried out of the bed. There is no longer a distinct visible bed level, but the bed become less and less dense through to the combustion chamber. The coarser entrained particles are separated in a hot cyclone and returned back to the bed.

The CFB-incinerator consist of three parts:

- The water-cooled furnace where the combustion takes place
- The hot cyclone to separate bed material from the flue gas coming out from the furnace
- Return leg with loop seal for circulating bed material

The primary combustion air is fed into the air wind box below the air distribution grid. Air flows from the wind box to the bottom of the furnace via air nozzles. The ash to be incinerated is fed in the loop seal. A part of the air is fed in the furnace as secondary air.

The reactor part is connected to the cyclone, which separates the circulating bed material from gases. The gas goes out from the cyclone to the back pass. The separated solids are led back to the reactor via the return leg and loop seal.

When combustion air enter under the solid bed, the gas velocity is so high, that the particles start to be fluidised. In this stage the bed expand and all particles are in rapid movement. The fluidising bed looks like a boiling liquid. The gas speed is so high, that part of the particles are flowing out from the reactor. The reactor contains lot of particles moving rapidly up and down. In this stage the reactor has excellent heat and material transfer properties. The temperature in this fluidising bed is 750 °C. The incoming ash contains about 30% combustibles and 70% ash. The ash enters the furnace blended with the circulating material. The char coal particles will be divided evenly into the fluidising bed, where the combustion starts. The circulating bed material serves as heat carrier and so it balances the temperatures in the process.

When the incinerator is shut down for long time, the incineration system including filter are conserved in the N_2 atmosphere to avoid the condensations and corrosion. The valves are closed. Bed material and ashes are taken out from the incinerator and silos.

The incinerator is hanging on the steel construction and the centerline of incinerator furnace is the fix line for the construction. The hot cyclone is supported on the steel construction also. The heat expansions in both will be take place freely downwards.

The incinerator bottom, cyclone and return pipe are refractory inside lined steel vessels.

The refractories inside are anchored in the steel shells and equipped with gas barriers in the refractories. The refractory lining is constructed in two layers.

The refractories are made of alkaliproof materials.

Limestone is used as bed material in the incinerator. In the low temperature the limestone is not calcined and is not pulverised in the circulating bed. Limestone is not reacting with alkalies and so is possible to avoid the agglomeration problems in the bed. The bed material feed capacity is adjusted according to the ash feed.

The fan is equipped with inlet silencer. The design of the fan is max 2.0 kg/s and maximum pressure increase 0.15 bar.

The combustion air fan control is e.g. via fan outlet valve control according to the required airflow, which is measured by the Venturi in the outlet duct.

5.12 Ash handling system

5.12.1 General description

The ash from the gasification plant will come from:
- The bottom of the gasifier
- The bottom of the gas cooler
- The product gas filters
- The ash incinerator filter
- The ash incinerator bottom

The ash handling system is included in the main process diagram in appendix 9.5.

All ashes, except the ash from the incinerator filter, will first be cooled in the cooling screws before those are treated further. The ash cooling screws are cooled with circulation cooling water. The shell and shaft in the screws are water-cooled. The ash from the incinerator filter will be discharged direct to the pneumatic conveying system.

The fly ash from the incinerator filter will be cooled and transported pneumatically to the fly ash silo. The fly ash from the silo will be sacked for the transport.

The bottom ash from the gas cooler can contain some larger clumps, which are removed by the sootblowers from the tube bundles. To ensure the problem free operation of the carbonic ashes there is a declumber after the cooling screw.

The ash from the gas cooler bottom and ash from the product gas filters contains so much unburned carbon and other hydrocarbon elements, so that those ashes have to be incinerated before those can be transported out from the plant.

The flyash from the gas cooler bottom and ash from the product gas filters contains also product gas. To ensure the safe handling of those ashes, product gas will be removed from those ashes in the gas change tanks. The ashes are fed into the gas change tanks, which are pressurised with inert gas twice and the gas is blown in the depressurising to the product gas filters. The carbonic flyash is transported with screw and elevator to the carbonic flyash silo. The carbonic flyash will be fed from this silo to the ash incinerator.

The cooled bottom ash from the gasifier will pass the declumber and rotary air lock feeder. After those the bottom ash will be send pneumatically to the ash silo.

The bottom ash from the incinerator will be collected to close ash containers. Normally this flow is very small.

5.12.2 Design and process values

The ash handling system consist of the following items listed:

- The Gasifier Bottom Ash Cooling Screw
- Rotary air lock feeder for bottom ash
- Declumber for bottom ash
- Pneumatic sender for bottom ash from the gasifier
- Gas Cooler Bottom Ash Cooling Screw
- Declumber for gas cooler ash
- The Filter Ash Cooling Screws
- The Transports Screw from filter ash and gas cooler bottom ash cooling screws
- The Gas Change Tanks with divert valve for incoming ash
- Change of the gas atmosphere
- The Drag Conveyor with inlet hopper from gas change tanks
- The Bucket Elevator from drag conveyor to char/ash silo
- The Char/Ash Silo
- Metering Screw from char/ash silo to the incinerator
- The Rotary Air Lock Feeder for the Incinerator feed
- The Feed Screw to the Incinerator
- Pneumatic Sender for fly ash from the Incinerator Filter
- Bottom Ash Cooling Screw from the Incinerator
- Rotary air lock feeder for incinerator bottom ash
- Fly ash silo
- Discharge screw from silo
- Ash moisturising baddle mixer

5.12.3 System description

The gasifier bottom ash:
The bottom ash from the gasifier bottom is sand like material with low carbon content (less than 1 %). The bottom ash contains normally only small amount dust. However this ash can sometimes contain clumps, where ash and bed material particles are agglomerated together.

The pressure drop of the gasification airflow through the fluidised bed will be measured. The gasifier bottom ash screw starts to operate, when the pressure drop over the fluidised bed is higher than the set point. The bottom ash system prevents the accumulation of bed materials too much in the fluidised bed. If the pressure drop has not reached the upper limit, the screw will operate 30 seconds twice in an hour. The cooling screw is a gas tight construction up to overpressure 1.3 bara. The shaft boxes are equipped with sealing gas rings. The material in the screw is stainless steel.

The rotary air lock feeder after the screw prevents the gasification air outflow in when the drain duct from the bed is not filled evenly with bottom ash. After the rotary air lock feeder there is a rotating declumper, which brakes the clumps below 25 mm in size.
The cooled and clump free bottom ash will be transported batchwise to the fly ash silo in the pneumatic feed system.

The carbonic flyash from the gas cooler bottom:

The Gas Cooler Bottom Ash Screw is operating continuously as well as the declumper after that. The declumper is a slow rotating crusher, which crush the ash deposit coming from the cooler to sizes below 25 mm.

The cooling screw is a gas tight construction up to overpressure 1.3 bara. The shaft boxes are equipped with sealing gas rings. The material in the screw is stainless steel. This carbonic fly ash will be mixed to the carbonic fly ash from the gas filters in the collecting screw.

The carbonic flyash from the gas filters:
Two double cooling screws are transporting the carbonic fly ash from the filters to the collecting screw. The shell and shaft are water cooled in the cooling screws. The material in the screws is stein less steel. The Cooling Screw from the bottom ash screw is operating continuously. The cooling screw is a gas tight construction up to overpressure 1.3 bara. The shaft boxes are equipped with sealing gas rings.

This gas cooler bottom ash will be mixed with the carbonic fly ash from the gas filters in the collecting screw. The Collecting Screw is not water-cooled. The material in the collecting screw is stainless steel and screw is a gas tight construction up to overpressure 1.3 bara. The shaft boxes are equipped with sealing gas rings.

The carbonic ash from the collecting screw will be divided in two lock hoppers, where the gas in the carbonic ash will be replaced with inert gas. The divert valve after the Collecting Screw will divide the fly ash to the lock hoppers.

When a lock hopper is filled with the fly ash, the inlet valve will be closed and the pressure in the lock hopper will be increased with inert gas to 4 bara. When the pressure is reached, the gas will be blown from the lock hopper to the gas duct before the gas filter. The lock hopper pressurising will be made twice.

The carbonic ash will drop down from the lock hoppers to the inlet hopper installed on the drag conveyor. The drag conveyor is a redler type. There is a slight under pressure in the inlet of hopper and drag conveyer.

The drag conveyor transports the carbonic ash to the bucket elevator, which lift the carbonic ash to the char/ash silo. There is a filter system on the silo keeping a small under pressure in the silo and conveyors after lock hoppers. The wall in the silo is carbon steel and the bottom cone is stainless steel.

From the silo the carbonic ash will be fed into the incinerator. First there is the measuring screw, which will control the feed in the incinerator. After the metering screw there is a rotary air lock feeder and transport screw in the incinerator. Small amount of inert gas (60 kg/h) will be injected in the rotary air lock feeder.

The incinerator bottom ash:
The bottom ash amount from the incinerator is normally very small and very fine sand like material with low carbon content (less than 2 %).

The pressure drop of the incinerator combustion airflow through the fluidised bed will be measured. The incinerator bottom ash screw starts to operate, when the pressure drop over the fluidised bed is higher than the set point. The bottom ash system prevents the accumulation of bed materials too much in the fluidised bed. If the pressure drop has not reached the upper limit, the screw will operate 30 seconds twice in an hour.

The rotary Air Lock Feeder after the screw prevent the combustion air outflow out, when the drain duct from the bed is not filled evenly with bottom ash.

The cooling screw is a gas tight construction up to overpressure 1.3 bara. The shaft boxes are equipped with sealing gas rings. The material in the screw is stainless steel.

The fly ash from the incinerator filter:
The fly ash from the incinerator filter is very fine dust and the carbon content is less than 5 %. The fly ash will be lead via a Rotary Feeder to the Cooling Screw and further to the to pneumatic Sender Vessel. This will send fly ash pneumatically with pressure air to the Ash Silo. The construction material is carbon steel.

The fly ash is collected to the fly ash silo, which is equipped with silo filter. The wall in the silo is carbon steel and the bottom cone is stainless steel.

The silo is equipped with discharge screw, which will transport the ash to the ash moisturising mixer.

5.13 Electrical systems

5.13.1 General description

The main principle of the electrical power distribution will be to deliver power supply to electric consumer: electrical equipment, variable speed drives, subcenters, and material which are delivered with the machinery. In the electrical systems are included distribution transformer, AC motors, low voltage switchgears, frequency converters, power and control cables, cable tray materials, earthing materials, local control and safety switches, sub-boards for service and maintenance, lightning and mountning. The apparatus and equipment comply with IEC recommendations.

5.13.2 Design and process values

The basis of design to the electrical equipment and drawings will be IEC recommendations valid on the day quotation and the mechanical dimensions are accordance with DIN.

All electric equipment are suitable for continuous use at the rated load at the ambient temperature of +35 °C. Switchgear and auxiliary equipment will be located in separate electric rooms, which must be ventilated.

The spaces of the plant will be classified to be normal areas, there is no danger of the hazardous areas.

Supply voltages to:
- The distribution transformer is 10 (6) kV 3-phase, 50 Hz isolated neutral earthed.
- The variable speed motors and motor drives are 690 (400) V, 50 Hz neutral point earthed.
- The lightning and maintenance is 230/400 V, 50 Hz, neutral point earthed.

5.13.3 System description

The transformers are oil-immersed, self-cooling type process distribution transformers according IEC-76 standard. Hermetically sealed type with corrugated tank and off circuit tap changer, porcelain bushings, oil level indicator, lifting hooks, pulling eyes, drain device with sampling facility, earthing terminals, rating and diagram plates.

The switchgears of 690 (400) V are of contact-protected and free standing construction. The protection class of switchgears is IP 20 and these conforms to the IEC-439 requirements. The switchgears and equipment will be dimensioned according to the load and short circuit currents. Switchgear feeders are standardised so that the motors of the same size have similar feeder equipment. Each motor contactor is provided with a thermal relay to protect the motor against over load and 2-phase running.

The motors are controlled from the DCS in the control room with local control switch located in the control circuit close to the motor. All AC-motors of low voltage are equipped with safety switch, which are connected to the main circuit and equipped with auxiliary contact for interlocking in the main circuit motors under 250 kW, over 250 kW there is control safety switch.

Measurements of 690 (400) V are in main switchgears. Switchgear supply cubicles are provided with 3 A-meters and a V-meter with changeover switch. Normally all the motor feeders are not equipped with A-metering. Motor feeders equal and over 37 kW are provided with current transformer and transducer for remote A-metering (in DCS).

The switchgears are provided to give the alarm of motor running to the control room in opposite principle. The alarm shows that the control situation does not comply with the operation.

10 kV power cables are non-armoured plastic insulated, sheath and of copper, standard IEC. 1 kV power cables are 3.5-core underground cables with copper conductors, plastic insulation and sheath. Cross-section of cables are selected to withstand the starting current of the motor and prevent too high voltage drop in a starting and running situation. Plastic insulated Cu-cables are used as controlling cables.

The principle is that the cables are mounted on trays. The trays are of galvanised steel. The control cables are fitted in bundles to save the space. Main cable trays have to be provided with 10 % reserve space for future mountings.

Electrical rooms are provided with a copper grounding bar to be connecting by a copper conductor of 120 mm² with frame ground. Motors and consumption equipment will be earthed through the protective concentric conductor of the supply cable. Switchgears, trays and other electrical equipment and building frames to be grounded are connected by a copper conductor of 16-50 mm² with the above mentioned copper bars.

The protection degree of motors is IP 56 and insulation class F, temperature rise according B, applied by IEC.

Lighting for boiler house and electrical rooms includes lighting fixtures, lighting centre, receptables, cables, trays and installation material for lighting.

5.14 Control & instrumentation system

5.14.1 General description

The instrumentation enables monitoring and automatic operation of the process from the control room through the control system man-machine interface. Instrumentation means to operate and display the process efficiently and safety. The process is furnished with measuring instruments to display such as pressure, temperature, level, flow etc. and control equipment. Distributed Control System (DCS) will be provided for the gasification plant monitor, control, display, alarm and record selected physical and electrical parameters.

5.14.2 Design and process values

The basis of design to the instrumentation and control system will be IEC, EN and ISO recommendations valid on the day quotation and the mechanical dimensions are accordance with DIN.

The DCS electronics will be located in the system room in the plant service building and the man-machine interface will be centralised in the control room.

Auxiliary power:
- Power supply alternative current 230 VAC / 50 Hz
- Pneumatic air supplies 6 bar(g)

Signal transmission:
- Analog signal 4-20 mA
- Pulse 0- 10 VDC
- Discrete 24 VDC
- Pneumatic signals 0,2 – 1,0 bar

5.14.3 System description

5.14.3.1 Instrumentation

Measuring instruments and control equipment will be selected for long term uninterrupted service. Local indicating pressure, temperature and level gauges will be located where such is deemed necessary or where it helps maintenance or ease trouble shooting.

Smart transmitters signal 4…20mA with superimposed digital communication (HART protocol) will be used where available. Digital communication is for diagnostics and transmitter tuning while mA signal conveys process variable data. Transmitters cannot be configured from the Distributed Control System Engineering station keyboard. Field instruments will be provided with manufacturer's standard IP 55 or better (NEMA 4 or 4X) protection.

Flow Measurements
Flow orifices and nozzles will be provided for water, steam and condensate flow measurements. ISO 5167 and VDI sheets 2 and 4 are applied for calculation and design of flow elements. The specific length for upstream and downstream paths will be specified according to ISO 5167. Primary element will be provided with tapping point isolation valves. Flow orifices material selection will be done according to pipeline material.

Differential pressure over a flow element will be detected with differential pressure transmitter.

Venturi tubes will be provided for combustion air flows. Differential pressure type flow measurements will be corrected with pressure and temperature signals in the DCS.

Fuel oil will be measured with “Coriolis” flow instrument.

Rotameters (variable area) will be provided to locally indicate flow, such as fluidising air and bearing cooling water.

Pressure and Differential Pressure Transmitters
Pressure and differential pressure transmitters equipped with local indication in transmitter housing will be provided. Transmitters will be connected to tapping point isolation valves with impulse piping or with diaphragm seal(s) and filled capillary tubing, depending on application.

Temperature Measurements
Resistance temperature detectors (RTD) will be utilised up to 300 °C whenever possible. RTD's will be 100 ohm platinum (Pt 100) sensors. For higher temperatures, such as boiler superheated steam and flue gas temperature measurements, K-type thermocouples will be utilised.

Level Measurements
Pressurised vessels will be equipped with differential pressure level transmitters. Condense pots will be provided where steam condensation will affect the measurement.

Solid material level in silos will be detected with radiometric or sonic measurements.

Local level gauges (gauge glass) on vessels containing liquid.

Solid Fuel Measurement
Solid fuel feed to the boiler is measured with radiometric weight scale on drag chain conveyor.

pH, conductivity, dissolved oxygen, sodium and silica
Analyser probes will be installed in flow chambers downstream sample coolers. Transmitters will be mounted remotely from the probes.

Oxygen (flue gas)
Quick responding in-situ zirconium type oxygen measurements will be provided for oxygen control.

Continuous Emissions Monitoring System
The system includes the following flue gas monitors:

- T — Temperature
- O_2 — Oxygen
- CO — Carbon monoxide
- CO_2 — Carbon monoxide
- SO_2 — Sulphur dioxide
- NO_x — Nitrogen oxides
- Dust content

The Continuous Emission Monitoring System (CEMS) meets requirements issued by local environmental monitoring authorities as well as EU requirements. Required factory and field tests will be conducted to provide certification of the installed system.

Motion sensors
Zero speed switches will be provided for the rotation monitoring of conveyor systems. These switches are used to alarm the operator and trip the conveyor system in case the electric drive monitoring system cannot detect the failure in the related process equipment.

Vibration Monitoring System and Bearing Temperature
Large rotating fans, pumps and associated medium voltage drives will be equipped with bearing temperature and vibration probes placed on bearing pedestals.

Control Valves and Damper Control Actuators
Valves will be sized to carry maximum nominal flow at the specified pressure drop with 80 % of valve maximum lift. Control valves and control dampers will be equipped with pneumatic actuators, electro-pneumatic positioners and mechanical position indicator. Upon the loss of power source, control actuators operate to maintain current control status or perform safety action.

Drives for Motor Valves and Dampers
Electric type on-off drives are equipped with open and closed position limit switches, open and close direction torque switches, a hand wheel and a local mechanical travel indication. Actuators are equipped with position transmitters where it's deemed necessary.

Installation
All field instruments and other components will be mounted in a location, which assures reasonable protection against mechanical damage, extremes of heat and cold or harmful vibration. The choice of location will also provide easy access for equipment maintenance. Generally remote located instruments will be mounted on prefabricated stands made of galvanised steel pipe. The stands will not be mounted on handrails, stairways, machine bases, process piping or to any location subject to severe vibration, sway or movement under load.

Cables will be installed in cable trays. Conduit will be used when cable departs from tray to individual instrument. The cables and tubing will be permanently identified at both ends with pre-fabricated plastic rings.

5.14.3.2 Control System

The plant is equipped with independent distributed control system (DCS). The DCS system is hierarchically structured with a high degree of automation. The control system enables to start and stop the main components from central control room, provides annunciation, open and close loop control, interlocks and assures of each component.

The DCS electronics will be located in the system room in the plant service building. The cross-connection will be located in the separate room under the system room. Man machine interface will be concentrated in the control room above the system room.

Distributed Control System (DCS) will be provided for the gasification plant monitoring and control. The system shall ensure safe, reliable and efficient operation of the plant. Dedicated control systems are avoided to maintain integrity and operational uniformity throughout the process. However for practical or safety reason some systems are specified as separate ones and not integrated in the DCS. Those systems are furnished with ability to communicate with the DCS. DCS supply shall include hardware, communication software and application software to monitor and remotely operate the dedicated systems. The DCS supply shall include Burner Management System and Boiler Safety System. These systems shall have TÜV approval for the mentioned application.

Following dedicated systems will be provided:
- Existing boiler DCS
- Fuel handling system
- Tube filter

Each dedicated system communicates with the DCS using serial interface link. Operator can monitor the plant operation through the DCS screens.

An integrated microprocessor based control and data acquisition system shall be provided to monitor, control, display, alarm, record and trend all assigned plant inputs and outputs. The

system shall have a distributed architecture comprised of independent functional processors (process station). Each functional processor shall be a configurable module programmed to execute a specific dedicated task.

The system includes independent process control utilising process I/O hardware. The process controllers to perform the necessary continuous, discrete and sequential control and data acquisition functions. CRT based operator interface in the control room including keyboards, printers and colorgraphic monitors.

Also programmer / engineer interface and historical storage and retrieval station.

Each system element will be designed such that a failure of any one element cannot affect the operation of any other element except for the loss of data from the failed element. The system shall be expandable and flexible and easily changeable via control engineer oriented software.

Redundant controllers with automatic failover shall be provided in DCS. A processor failure shall be alarmed on the operator's desk.

Independent processors for Burner Management System as well as for Boiler Safety System shall be provided i.e. these processors shall be dedicated to their main tasks and no other functions shall be implemented in these processors.

Security of communication shall be assured by use of a redundant highway, a proven highway protocol and system-wide diagnostics that are designed to detect faults and indicate recovery actions transparent to the operator. Each drop shall have universal access to all process points variables system-wide.

All of the drops in the system shall be built from common parts. In additional to common hardware, common software philosophy shall be used in the elements.

The system will be capable of being expanded by adding more drops to the system. The addition of drops shall not affect the functions operating in existing drops nor does it shall degrade the performance of the existing system.

All gasification plant operational data is presented on DCS CRTs to the operator. Modulating, discrete and sequential controls shall be integrated in the DCS. The DCS control logic shall include advanced control modes. For the dedicated controls, with independent controllers, the operator interface is in the DCS i.e. the operator monitoring, advanced controls and set point development for the dedicated controllers is carried out in the DCS modules.

5.15 Operation philosophy

The control philosophy of the gasification plant has been estimated in the following cases:

1. Normal operation
2. Start up
   2.1. Start up in cold conditions
   2.2. Start up in hot conditions
3. Stop of the plant
   3.1. Normal stop
   3.2. Stop in disturbances
4. Disturbances

In the operation procedures the following principles have been taken into consideration:

1. Safety operation
2. Simplified sequences
3. Simple action to avoid the consequences of the disturbances
4. The multiple measurements of the important values or detection of important actions

The gasification plant is divided in the systems, which are controlled as blocks. There is also a separate safety system, which is a doubled system and installed in a separate cabinet. Only entitled persons can open it and make modification there.

The control and function analysis of the systems are divided in the following:

a. **Gasification system**, which includes the gasifier, air supply and distribution, start up burner and air preheater
b. **Straw feed system**, which includes the windscreens, pneumatic transport equipment, transport air cleaning devices, plug screws, plug looseners, gate dampers and feed in screws
c. **Wood feed system**, which includes the receive station, conveyor to silo, silo, pneumatic transport equipment, feed bins with double screw dischargers and the double rotary valves
d. **Bed material system**, which includes the storage silos for sand and limestone, pneumatic transport equipment to dosing silos, dosing silos to gasifier and incinerator with dosing equipment
e. **Feed water system**, which includes the gas cooler, feed water pump, preheater, incinerator cooling circuit and piping
f. **Product gas system,** which includes the filters, gas ducts, gas valves, gas burners in the main boiler, steam tracing and flare
g. **Flyash incineration system,** which includes the CFB boiler with hot cyclone and loop seal, air feed equipment, back pass, flue gas filter and fans
h. **Ash handling system,** which includes the bottom ash cooling screws with rotary air lock feeders for gasifier and incinerator, declumper and pneumatic transport equipment for gasifier bottom ash to ash silo, cooling screws for the carbonic filter and gascooler ash, declumper for cooler ash, collecting conveyor for carbonic filter ash and gascooler ash to gas change vessels, gas change vessels, conveyors from gas change vessels to carbonic ash silo, silo, discharge and feed equipment for the carbonic ash feed in the incinerator, pneumatic transport equipment for fly ash from the incinerator flue gas filter to ash silo, ash silo, discharger from silo and moisturising screw for ash
i. **Control & instrumentation system,** which includes the DCS system and field instruments
j. **Electrical systems**

5.16 Safety aspects

5.16.1 General

The gasification plant will be constructed to be safe for:
- Environment
- Operators
- Equipment

The design of the plant will be made according the local laws and safety rules. The design of the plant will be checked in the safety analysis. The specific method, which will be utilised in the safety analysis, will be specified later.

The identified risks in this type plant are:

- Intern explosion in the process
- Release of toxic and flammable gases
- Fire in the plant

The design of the plant will be performed so, that each System will be documented in the System Descriptions. Based on those descriptions the Function Analysis of each system will be made. In the design work the Safety Analysis are performed at the same time as the Function Analysis. Before the design can be approved, the written Safety Analysis Document should exist.

In the plant control system will be the Safety Interlocking System, where all important safety interlockings are programmed. The rules how the Safety Interlocking System will be constructed will be agreed later. The Safety Interlocking System will be realised so, that only the authorised persons can make the possible modifications.

The consequences of each possible accident will be classified in the Safety Analysis. The most dangerous cases, where the consequences are serious, the safety systems will be multifold.

5.16.2 Design principles

Layout:
The fuel treatment systems (straw and wood) will be located nearby the gasification plant. However there has to be enough space for the fire brigade to separate the fuel yards from the gasification plant in the case of fire.

A layout drawing of the straw gasification plant is shown in appendix 9.6.

Fuel feed:
The fuel feeds to the gasification plant will be performed with pneumatic conveying. Air is used as transport medium. The fuels are normally so coarse, dust explosion is not possible. However there can be also dry dust, which is explosive. So the cyclones in the pneumatic feed systems will be furnished with explosion doors. The explosion directions are upwards on the top of the plant.

Also the silos and bins in the fuel feed system will be equipped with sprinkler systems. Steam is used in the feed bins to purge air out from the bins. The feed bins will be discharged empty to the gasifier in the steam atmosphere.

Gasification plant:
The gasification plant will be in small overpressure all the time. This means, that air is not flowing into gasification plant. Air and product gas mixture can be explosive. Air is fed in only into the hot CFB gasifier. In hot fluidising gasifier air is reacting with straw and explosive mixture is not formed.

However the parts where cooled gas exist (e.g. filters) will be furnished with explosion doors. The gas cooler will have a weakened corner.

The gasification systems will be made gas tight. The number of flange joints will be minimised and the tightness of the plant will be checked after modifications and maintenance.

Inert gas is used to purge product gas out from the plant to the main boiler. Also steam is used in the gasifier and gas cooler, when the plant is still hot.

The gasification plant and the gas burners will be furnished with CO-detectors to find the possible gas leaking.

Materials:

Gases:
- Product gas (toxic and flammable)
- Nitrogen (risk to suffocate)
- Natural gas (flammable)
- Steam (hot and high pressure)
- Air (hot)
- Fluegas (hot)

Liquids:
- Cooling water
- Feed water (hot and high pressure)
- Lubricating oils (fire risk)

Solids:
- Straw (fire risk, dust explosive)
- Wood (fire risk, dust explosive)
- Carbonious Fly ash (fire risk, dust explosive)
- Bed materials
- Bottom ash
- Fly ash

5.17 Concluding remarks

The result of the Design Study combined with the result of the Process Validation shows that it would be technically realistic to built and operate a 100 MW_{th} straw based CFBG connected to a modern fossil fuel based CHP plant. All processes and technical solutions have been thoroughly assessed and there have not been found any technical show-stoppers.

There are, however, certain technical and operational uncertainties connected to scaling up the fuel system, gas cleaning train, product gas distribution to the boiler and filter ash oxidation. The uncertainties are related to both scaling up the process/equipment and to long term operation. Most of these could be reduced considerably by further development and testing.

Fuel preparation and feeding could be built and cold tested in full-scale. Long term testing is not realistic because of the “mountains” of loose straw that would have to be handled. Long term testing of the gas cleaning train could be done in small scale by taking a slip-stream of product gas from a commercially operating gasifier, and run it through a small test rig with gas cooling and filtering. The largest uncertainty is related to oxidation of filter ash. The CFB combuster makes it possible to reach the environmental limits, but the process is too complicated and is expected to give operational problems.

The partners recommend that actions are taken in order to build up more operational experience with the technical fields in question, and to develop a more simple and reliable process for oxidation of filter ash.

6. CAPITAL AND OPERATION EXPENSES

6.1 Introduction

In this chapter capital and operational expenses are calculated for the two possible sites in E2´s production system. These are the coal fired CHP units AMV3 (Amagerværket) and AVV1 (Avedøreværket) placed in the Copenhagen area. The units are identical and all calculations are valid for both.

A gasifier can easily be connected to the existing boilers. Only storage for straw or straw and wood should be established near to the gasifier. In figure 6.1 is shown the connection between the gasifier and the CHP-plant.

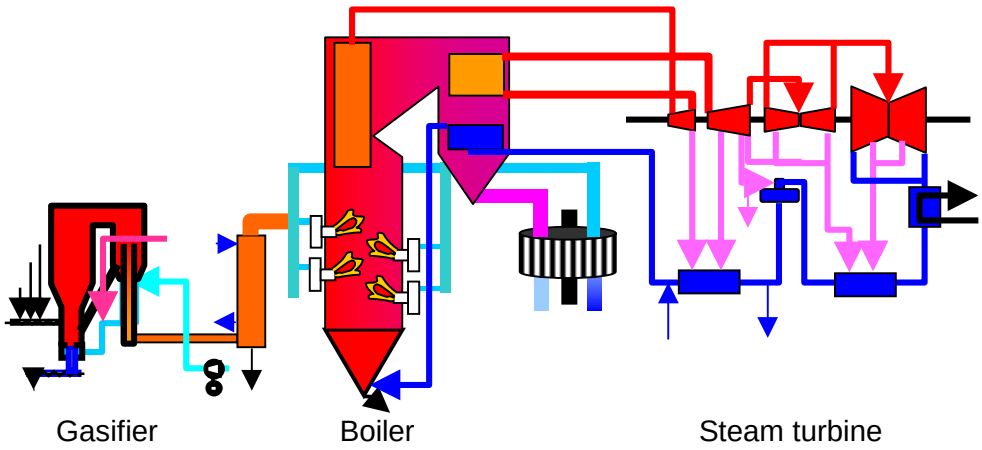


Figure 6.1 Gasifier and CHP-plant

The current electrical efficiency of AMV3/AVV1 in condensing mode during coal firing operation is 42,1 % and during back pressure mode 35,8 %. The marginal electrical efficiency of straw gasification is at 100 % load and condensing operation 39.3 % and for wood chip gasification 33,5 % (wood chips has a moisture content of 45 %). In back pressure operation the marginal electrical efficiencies are respectively 32,8 % for straw and 27,0 % for wood chips.

All calculations are made on the basis of constant prices. It is very important to notice that all prices on fuel purchase and sales prices of heat and electricity are based on present Danish conditions and prices that only apply to the two units dealt with.

6.2 Capital expenses (CAPEX)

6.2.1 Assumptions

The prices specified in the budget are based on budget prices from Foster Wheeler, on prices obtained from potential suppliers and on estimates from similar projects implemented by E2.

Capital expenses are expressed in constant prices (in EURO million) as at April 2001. The calculations break down capital expenses so that 10% will be due in 2003, 60% in 2004 and the remaining 30% in 2005.

As the plant is expected to be set up at the prices specified in the capital budget and since

the prices are broken down as indicated above, calculating the net present value (NPV) of capital expenses will cause prices in 2001 to be lower than those specified in the capital budget.

Creating a time lag between capital expenditure and operating income, the calculations will automatically include interest during construction.

The following financial parameters were used for the operational calculations:

- Period of depreciation 20.00 years
- Real interest rate 5.00 % p.a.
- Inflation 2.50 % p.a.

The year 2001 is used as the basis of all calculations. The first full year of operation in the calculations is 2006. Calculations subsequently cover a period of 20 years up to and including 2025.

6.2.2 Capital budget for 103 MW_{th} straw ACFB gasifier

- Mechanical works 18.8 MIO. EUR
- Electrical works 4.1 MIO. EUR
- Civil works 5.0 MIO. EUR
- Engineering etc. 7.0 MIO. EUR
- Subtotal 34.9 MIO. EUR

- Contingencies, 10 % 3.5 MIO. EUR
- **Gasifier plant total (for straw) 38.4 MIO. EUR**

6.2.3 Capital budget for 103 MW_{th} straw and wood ACFB gasifier

- Additional expenses for wood chip plant 3.9 MIO. EUR

- **Gasifier plant total (for straw and wood) 42.3 MIO. EUR**

6.3 Operation expenses (OPEX)

6.3.1 Assumptions

Annual operating hours
Both the gasification plant and the main unit are assumed to be in operation for 6,000 equivalent full-load hours per year.

Fuels

- Calorific value of straw at 14% moisture content 14.8 GJ/tonnes
- Calorific value of wood chips at 45% moisture content 9.2 GJ/tonnes

It is assumed that slag and ash from the straw plant can be returned to the individual farmer and that slag and ash from the wood chip gasification process can be returned to woodland areas.

6.3.2 Fuel prices

The calculations are based on a straw price of EUR 5.6/GJ (EUR 83.1/tonne) using the year 2001 as a basis. Current prices are adjusted by an annual inflation-related increase of 1.5%, compared to an annual standard 2,5%, since the effect on straw and wood chip prices is expected to drop through improved methods of straw production as well as better modes of transportation. If converted into fixed prices at an annual inflation rate of 2,5%, prices will actually fall in real terms.

The calculations are based on a wood chip price of EUR 4.3/GJ (EUR 40.2/tonne).

Since the gas substitutes coal in the boiler, the expense saved by reduced use of coal is deducted in the economic calculations. The coal price is fixed at EUR 1.3/GJ.

6.3.3 Operating and maintenance expenses, excluding fuel

The operating and maintenance expenses of straw-fired power plants can be broken down into the following items:

- Fixed operating expenses (wages and salaries)
- Administration
- Variable operating expenses (limestone, sand, water, filter bags)
- Fixed maintenance expenses (buildings)
- Variable maintenance expenses (machinery and plant)

Annual fixed operating expenses
The gasifier is operated from the central control room. Additional manpower at the plant dedicated to the gasifier is assumed to be as follows:

- On a daily basis (skilled worker) 1 person
- Straw barn (unskilled labourer) 4 persons

A combined straw and wood chip gasification plant requires 1 additional unskilled labourer.

Annual administrative expenses
Administrative expenses are estimated to account for 10% of fixed operating expenses.

Annual variable operative expenses
The calculations are based on a sand consumption of 0.067 kg/s for straw gasification (0.051 kg/s for wood chip gasification) at a price of EUR 32.0/tonne and a limestone consumption of 0.133 kg/s (0.099 kg/s for wood chip gasification) at a price of EUR 51.3/tonne. Prices were obtained from I/S Midtkraft, DK.

The consumption of second-rate water is expected to be 0.05 kg/s at a price of EUR 0.7/m³. The water consumption for wood chip gasification is 0 kg/s.

The consumption of steam for moistening gasification air is estimated at 0.8 kg/s, causing the consumption of deionate to be 0.8 kg/s at a price of EUR 1.4/m³. The gasification air for wood chip gasification need not be moistened, causing the consumption of deionate to be 0 kg/s.

The consumption of inert gas (N_2) is expected to be 300 kg/hour and 2,000 kg/stop. On the basis of 10 stops a year and 6,000 operating hours, consumption is estimated to be 1,820,000 kg/year. The price of inert gas is estimated to be EUR 27/tonne.

Price estimation for replacing filter bags is EUR 612,000. With right design and operational parameters, the lifetime is expected to be 1-2 years.

At 6,000 full-load operating hours and at an annual straw consumption of 150,000 tonnes, the variable operating expenses will be EUR 4.5/tonne. At an annual consumption of 75,000 tonnes of straw and 120,000 tonnes of wood chips, the variable operating expenses will be EUR 3.2/tonne.

Annual fixed maintenance expenses
The fixed maintenance expenses of the straw plant (building, site, etc.) are estimated to account for 0.50% of the expenses incidental to buildings.

Annual variable maintenance expenses
The variable maintenance expenses (machinery and plant) are estimated to account for 2% of machinery and electricity plant investment.

6.4 Calculation of income

All calculations of income are based on Danish rules connected to the Copenhagen area. This rules can change and can only be considered to be valid until mid of 2001.

6.4.1 Assumptions

Operational calculations are made for the following modes of operation:

Plant using 100% straw as a fuel (150,000 tonnes/year)
Plant using 50% straw and 50% wood chips as a fuel (75,000 + 120,000 tonnes/year)

These calculations are made as marginal considerations in relation to using as a fuel coal in the main boiler, meaning that only additional and lost income/expenditure for the plant are included.

Operational calculations are made each year over a period of 20 years. Income includes the sale of electricity and heat, while operating expenses include expenses incidental to fuels, operation and maintenance. Changes in emission taxes are also included, and the contribution margin for the plant is calculated on this basis. Capital expenses are deducted from the contribution margin. On this basis, the accumulated NPV of the plant is calculated over the entire period of depreciation.

On the basis of the future penal tax of EUR 5.4 levied on every tonne of CO_2 emitted in excess of the CO_2 quotas, this amount is included as the value of CO_2 saved when biomass is used. Yet this indirect tax is calculated only for CO_2 emissions from fuel used for generating electricity (and not heat), since it currently looks as if only fuel used for generating electricity will be subject to a penal tax. The volume of fuel used for generating heat is calculated on the basis of a fixed thermal efficiency ratio of 200%. Note that this thermal efficiency differs from that of 125%, which is used for calculating tax to be levied on fuel used for generating heat.

6.4.2 Sale of electricity

The market price of electricity is fixed at EUR 21.4/MWh which is regarded as a future average market price on the Nordic market, but it may vary of course, depending on the market situation.

The price of electricity generated by straw gasification will be EUR 40.2/MWh (guaranteed price) for the first ten years plus EUR 13.4/MWh from the sale of renewable energy certificates (RE certificates), totalling EUR 53.6/MWh. The price of EUR 40.2/MWh is deflated because the guaranteed price is not written up in tandem with inflation. The price of EUR 13.2/MWh from the sale of RE certificates is the guaranteed minimum price (maximum price: EUR 36.2/MWh).

After the first ten years, the market price of electricity from straw gasification is fixed at EUR 21.4/MWh plus EUR 13.4/MWh from RE certificates, totalling EUR 34.8/MWh.

Since the gas from straw gasification replaces coal firing to some extent, the reduced electricity production and thus coal-based electricity sales at market prices have been deducted from the electricity income generated by straw gasification.

6.4.3 Sale of heat

The heat price for the CTR/VEKS heating transmission companies is fixed at EUR 1.7/GJ. This price is only valid for production of heat in CHP-plants in greater Copenhagen area.

The price of heat generated by straw gasification is increased by the taxes saved, which are imposed on heat generated by coal-fired plants. These taxes are:

• Energy tax		EUR 6.80/GJ
• CO_2 tax	EUR 32.4/tonne =	EUR 1.30/GJ
• SO_2 tax (98 % reduction in desulphurisation plant)	EUR 1.3/kg =	EUR 0.02/GJ
Total		EUR 8.12/GJ

Given the present circumstances, the required thermal efficiency is 125%. This will reduce the tax to EUR 6.5/GJ.

The price of heat generated by straw gasification is therefore EUR 1.7 + EUR 6.5/GJ, totalling EUR 8.2/GJ.

The reduced sales of coal-based heat are deducted from the income from straw-based heat.

6.4.4 Results of operational calculations

Investment in a **gasifier (100% straw)** of EUR 38.4 mio., generates an NPV of minus EUR 1.4 mio. (see assumptions in appendix 9.1 and calculations in appendix 9.2). The NPV for each year can be seen from figure 6.2 below.

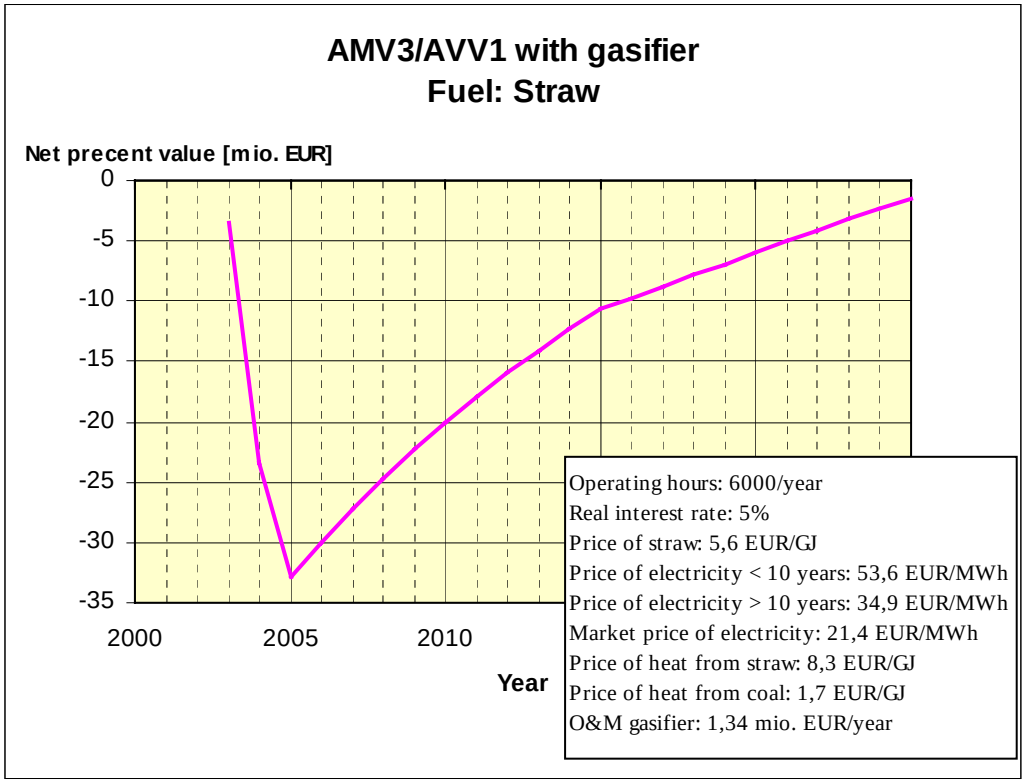


Figure 6.2 NPV over the years for a gasifier (100% straw) at AMV3/AVV1

Investment in a **gasifier (50% straw and 50% wood)** of EUR 42.8 mio., generates an NPV of 7.0 mio. (see assumptions in appendix 9.3 and calculations in appendix 9.4). The NPV for each year can be seen from figure 6.3 below.

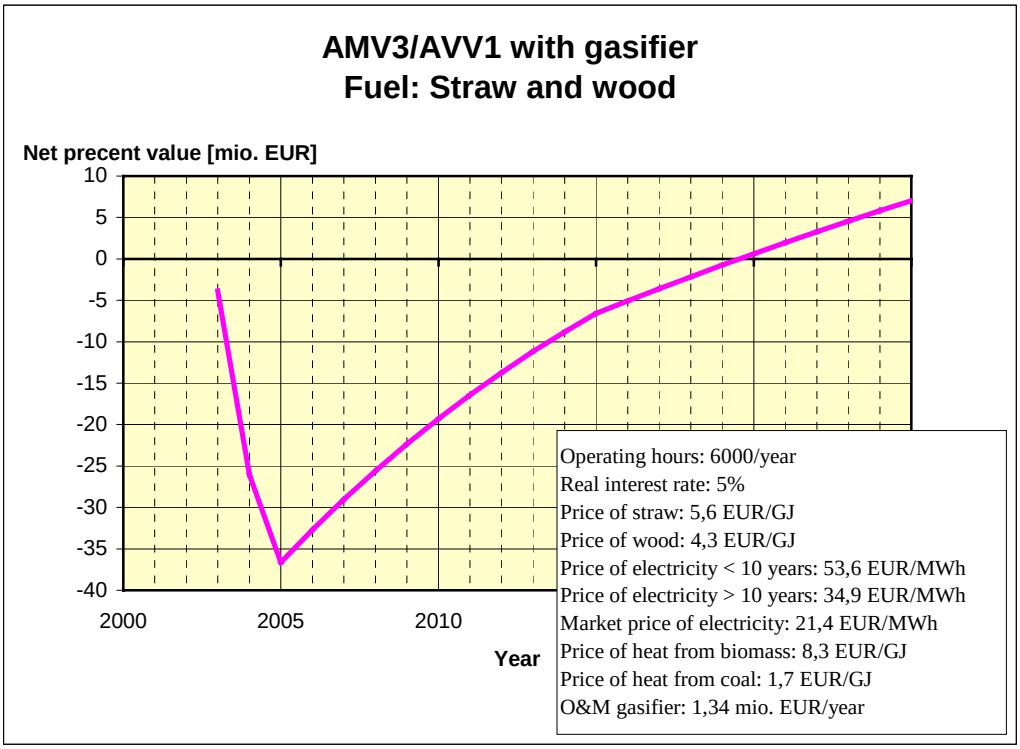


Figure 6.3 NPV over the years for a gasifier (50% straw and 50% wood (45% H_2O)) at AMV3/AVV1

6.5 Concluding remarks

Fig. 6.2 and 6.3 shows the resulting NPV over the years for a 100 % straw-fired gasifier and a 50/50% straw and wood chip-fired gasifier at AMV3/AVV1. In both cases the start of gasification is the year 2005.

In these actual analyses only the case of firing 50/50 % straw and wood chips generates a positive NPV over 20 years. The main reason for these relatively low benefits of using a gasifier is a very low price of heat produced in the Copenhagen area and very high prices of straw. Another reason for these results is expensive equipment for the gas-cleaning part and for treatment of filter ash. These expenses can only be relevant when using fuels as waste, that also in known techniques has to be burned in units with advanced flue-gas cleaning systems.

7. ELEMENTS IN THE APPROVAL PROCESS BY THE AUTHORITIES

7.1 Residuals

In connection with straw gasification in a fluidised bed plant, the residual will consist of a mix of ash and bed material. The following carbon content for the residue is results from the tests:

Content	% in bottom ashes	% in filter ashes	% in filter ashes after combustion
Straw ash, sand and limestone compounds	99.85	74	96
Carbon (unburned)	0.15	26	4
Total	100	100	100

Table 7.1. Carbon in residual

The quantitative ratio between bottom and filter ash were in tests approx. 30/70% (calculated based on the mass flow), which ratio is almost the opposite of that seen in conventional straw-fired plants (20/80%).

The residual quantity in connection with burning of 150,000 tonnes of straw annually will be about 3,500 tonnes of bottom ashes and 8,200 tonnes of filter ashes, in total 11,700 tonnes of residual to bring back to the fields.

7.2 Environmental legislation

7.2.1 Polyaromatic Hydrocarbon (PAH)

This ash can be used in agriculture in accordance with the Danish Order on use of ash from biomass and biomass waste gasification and burning in agriculture. The order came into force on 1 February 2000. The residual should however meet the order's requirements to heavy metal content values. However, it is still uncertain whether the "threshold value" for PAH can be met. The threshold value for PAH is 3 mg per kg dry solids (DS). If the residual carbon content in the ashes exceeds 5%, the residual must be analysed for PAH in connection with every heavy metal analysis – i.e. up to four times a year.

Tests conducted in Finland have shown carbon contents in the ashes of about 26% and PAH content exceeding 100 mg pr kg DS. Foster Wheeler therefore tried to combust the filter ash in a CFB boiler for reducing the organic substances and PAH in the fly ash. With "post burning", the PAH level reduces 0.8-1 mg/kg. The threshold value of 3 mg PAH per kg DS as stipulated by the bio-ashes order is thus likely to be attained.

7.2.2 Heavy metals

The critical heavy metal in straw ash is cadmium (Cd). 0.5-5 mg cadmium is allowed per kg DS, and the spreading quantities allowed lie between 5 tonnes per hectare every 5th year and 0.5 tonnes per hectare every 5th year where the cadmium content is highest.

In terms of mixed straw and wood-chip ash, a "minimum limit" has been introduced, so that input of up to 25% wood with the straw is considered and can be treated as pure straw ashes.

In practice, the farmers are unable to spread so small quantities as 0.5 tonnes per hectare. Therefore, ENERGI E2 maintains the systems for separating bottom and fly ash on the

straw-fired plants currently in operation, to meet the maximum Cd content of 2.5 mg/kg DS, which permits spreading maximum 1.5 tonnes of DS per hectare every 5th year.

For the straw based CFBG both filter and bottom ash have Cd levels that are below 2.5 mg/kg DS. This means that the total ash stream (filter plus bottom ash) can be brought back to the fields fulfilling the limits for spreading maximum 1.5 tonnes of DS per hectare every 5th year.

7.2.3 Other environmental aspects

The pH value of the residual will be 10-12, which is almost the same as the pH in wood ashes, which Swedish studies have shown to be 10-13. The low pH value has not yet proved a problem in agriculture or forestry, because the product can replace liming with agricultural liming materials and because farmers are only allowed to spread small quantities: 0.5 to max. 5 tonnes of straw ashes per hectare every 5th year on farmland and 0.5 to max. 7.5 of wood ashes per hectare every 10th year in forestry. The content of the heavy metal cadmium decides the quantity to be spread.

The low pH value can of course have harmful effects on the crops in the form of “scorch” in the same way as other acidic or alkaline products, and residual should therefore be avoided on growing crops. One way of reducing the problem could be to granulate the product, which would also solve the problems concerning flying dust and health and safety.

7.3 Environmental assessment and licensing by the authorities

7.3.1 General

The establishment of a gasification plant requires thorough handling by the authorities. The handling concerns authorisation pursuant to the Danish Electricity Supply Act, which is granted by the Danish Energy Agency, and authorisation pursuant to the Danish Planning Act and the Danish Environmental Protection Act, which is granted by the county.

Authorisation in accordance with these acts must have been granted before an application for planning permission can be submitted with the local authorities.

7.3.2 The Electricity Supply Act

Establishment of CPH plants (production units) is regulated by the Electricity Supply Act. According to Act no 375 on Electricity Supply, a grant recipient, cf. section 11, must have an authorisation to establish new production plants:

Section 11. Establishment of new electricity production plants and substantial changes to existing plants are only allowed subsequent to prior authorisation by the Minister for Environment and Energy.

Subs. 2. Granting of authorisation is contingent on the applicant documenting compliance with specified published conditions regarding the energy efficiency, use of fuels and general environmental aspects of the plant to which the application pertains.

Establishment of plants for straw burning/gasification can form part of the rules for complying with the biomass agreement concluded on 14 June 1993 and amended in 1997 and 2001.

7.3.3 The Planning Act and Environmental Impact Assessment (EIA)

According to the Planning Act s. 6 and Order no. 428 of 2 June 1999 regarding supplementary rules in pursuance of the Planning Act, the regional development plan must include guidelines for location and design of large technical plants assumed to have a considerable impact on the environment.

For combustion plants with an input efficiency exceeding 120 MW (a so-called schedule 1 plant), the guidelines in the regional development plan must be accompanied by an assessment of the plant's impact on the environment (EIA).

The same applies to plants falling within the order on risk control of major accidents with hazardous substances, regardless of the size of the plant. Whether a gasifier falls within the section 4 category in the order depends on how the straw gas is categorised, e.g. in relation to the danger of explosion.

However, the plant must in any circumstances undergo a "screening", which is to provide answers to whether the environmental impacts are of a magnitude calling for an EIA procedure. The county performs the screening, but in practice the applicant company supplies the information.

The screening includes the following overall criteria, cf. schedule 3 of the order:

- The project's characteristics in relation to dimensions, cumulation with other projects, use of natural resources, waste production, pollution and risk of accidents.
- The project's location in relation to present land use and the capacity of the natural environment, etc. with a view to protecting natural resorts and areas where the established environmental quality norms have already been exceeded.
- Symptoms of the potential environmental impact with regard to the extent and possible transboundary characteristics of the impact, impact ratio and complexity, duration, frequency and reversibility, etc.

The county's decision as to whether the project necessitates an EIA must be published together with its reasons for its decision.

If the county determines that the project does need an EIA, an EIA report must be prepared containing the information stated in schedule 4 of the order, which can be summarised as follows:

- Description of the planned extension both in relation to the construction and operation phase.
- Outline of alternatives and description of the zero-solution (the solution where the plant is not extended).
- Description and assessment of the surroundings affected by the plant.
- Description of the plant's impact on the environment in relation to water, air, noise and consumption.
- Description of measures used to reduce the environmental impacts.
- Non-technical summary.

The time spent on realising the EIA procedure and until the final approved regional development plan supplement is available is typically 1-1½ year.

7.3.4 The Environmental Protection Act, Chapter 5 and IPPC companies

IPPC (Integrated Pollution Prevention and Control) is an EU directive that entered into force in Denmark on 3 November 1999 and applies to all industrial activities including power stations with a total effect exceeding 50 MW. The objective of the directive is to ensure a

more sustainable balance between human activities and economic development, on the one hand, and the nature's resources and regeneration ability, on the other hand. The directive requires the "best available technique" to be applied and the authorities to revise the environmental authorisation every 10th year. The directive also emphasises waste minimisation, i.e. waste should be avoided entirely, and where this is impossible, waste should be recycled to the greatest possible extent. The new rules mean that all large companies in the EU must have an environmental authorisation under the same rules.

Establishment of a straw gasification plant requires environmental authorisation pursuant to Chapter 5 of the Environmental Protection Act.

The environmental application must include the following information:

- Ownership and responsibility
- Type of company, location and establishment
- Drawings and descriptions of the company's lay-out of premises and production
- Choice of location and best available technique
- Pollution and pollution limiting measures concerning air, wastewater, noise, waste, soil and groundwater
- Access and exit
- Proposal for conditions and internal inspection.
- Information regarding system breakdowns and accidents and, as a new measure
- The information in the application must be summarised in a non-technical summary

The time limit for filing complaints before the authorisation is finally approved is four weeks from the publication of the environmental authorisation. It is possible to complain about the authorisation to the Danish EPA. However, in principle, this will not have a delaying effect.

In accordance with the new Environmental Protection Act and a new guide on approval of licensed sites (including IPPC companies), environmental applications must be published before the approving authority starts reviewing the case. The public must have 3-6 weeks to comment on the application. This means greater time consumed on the authorisation procedure. The new guide came into force on 30 October 1999.

If the plant is to undergo an EIA procedure, this will replace the publication of the environmental application.

Summarising the licensing process

A gasification plant with a size of 100 MW_{th} shall obtain the following permits and approvals:

- Authorisation according to the Electricity Supply Act
- Authorisation according to the Environmental Protection Act (Chapter 5 authorisation)
- Authorisation according to the Planning Act, which includes local and the regional development plan and
- EIA (Environmental Impact Assessment). Whether a 100 MW_{th} gasification plant necessitates an EIA will depend on e.g. where the plant is desired to be localised and the specific design of this. However, the plant must in any circumstances undergo a "screening", which is to provide answers to whether the environmental impacts are of a magnitude calling for an EIA procedure.

8. EVALUATION AND CONCLUSION

8.1 Basic conditions

Before a decision to built a straw fired atmospheric CFB with gas cleaning can be taken, some conditions have to be full filled.

Some of these are as follows:

- More capacity to use straw should be needed in the production system
- Straw for the new unit should be available on the market
- An atmospheric gasifier with gas cleaning should be able to compete economically and environmentally with already known technique
- The amount of technically uncertainties should be limited to areas where the risks are comparable to already known technique

In the following some more details about project economy and technical uncertainties will be described.

8.2 Project economy

The project economy has been calculated for two actual cases valid for E2´s production plants AMV3 and AVV1 both coal fired and with boilers able to burn gas from a gasifier. The results obtained are depending on the price of fuel, heat and electricity valid for these two plants. If the gasifier is connected to other units placed at other sites or in other countries with lower prices on fuel (straw and wood) and higher prices of heat and green electricity, the result could easily be much more positive.

Capital budget for a 103 MW_{th} complete straw gasifier coupled to a boiler all incl. is EUR 38.4 mio. For a 103 MW_{th} 50/50% straw and wood chip gasifier the equivalent budget is EUR 42.3 mio. The higher price in the case of straw and wood is due to additional expenses for the handling and storage of wood chips.

Calculations covering a period of 20 years shows that the generated NPV for 100% straw is minus EUR 1.4 mio and for 50/50% straw and wood EUR 7.0 mio. Considering the large uncertainties involved, the economic conditions obviously are not good enough for an investor to consider such a project.

8.3 Technical uncertainties

The actual gasification process with gas cleaning has already proved to be technically feasible during the tests performed in the 3 MW_{th} gasifier described in this report. An overview of the testing gives the following results.

Four test series have been conducted of which point 1 and 2 were carried out prior to the commencement of STRAWGAS project.

These are:

- Running in of test pilot plant with straw pellets.
- Tests with loosely cut straw and a specially designed feeder.
- Tests with loosely cut straw. Long term testing with gas cleaning etc.
- Burning of filter ashes in a low-temperature CFB.

Totally 330 t of straw has been gasified in 500 hours. 110 t was straw pellets and the rest of 220 t was loose straw from ordinary Hesston bales.

With basis in the work performed, it can be concluded that the following processes are proved to be technically feasible:

- Loose straw can be transported pneumatically from straw loosener in straw storage to straw feeder at gasifier
- The special developed straw feeder can both feed straw at constant flow into the gasifier and establish an air tight lock between the inside of the gasifier and the outside
- Gasification of straw is possible with an efficiency of 95 %
- The gas can be cooled in a cooler after the gasifier
- In a fabric filter the cooled gas can be cleaned for dust and Cl, K and dust can be removed
- The cleaned gas is finally easily burned in a conventional gas burner
- The ash from the filter can be burned in a low temperature CFB, and the 25-30 % content of carbon can be reduced to below 5 %

Furthermore the design study with a view to create a design basis for a 100 MW_{th} demonstration plant has given detailed solutions for the following main areas:

- Main process description, including a flow-chart
- Process safety measures
- Description of the gasifier. The gasifier will largely resemble the Lahti gasifier of approximately 70 MW_{th}
- Gas cooler and gas cleaning system.
- Description of connection system to the existing boiler and relevant burner design
- Wood-chip and straw feeding system
- Wood-chip and straw storage facilities
- Nitrogen system
- Ash processing and handling system
- Electric systems
- C&I systems
- Buildings
- Operating philosophy

A plant design already exists and most of the above items have been tested and satisfactory solutions have been found.

Still there are technical uncertainties and as a consequence also possible economical risks with scaling up from 3 MW_{th} to 100 MW_{th}.

FWE has already built a lot of CFB boilers using biomass as fuel, and there is good experience running those plants. The thermal input of these units is well above 100 MW_{th}.

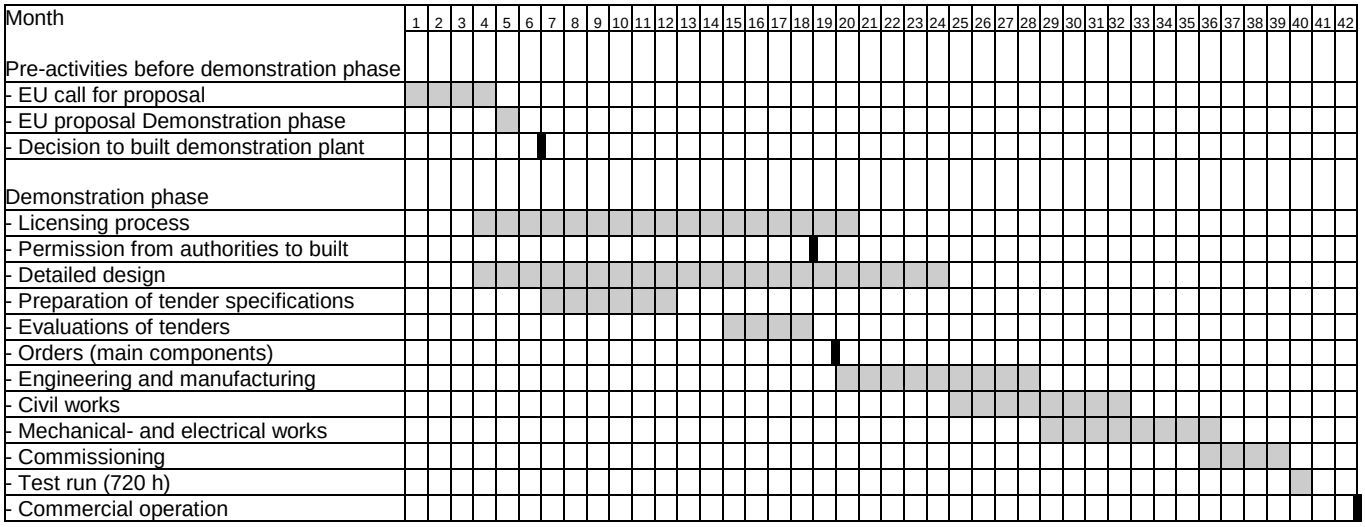
FWE has built 4 CFBG during the eighties (15-35 MW_{th}) and more recently an atmospheric gasifier in Lathi using RDF as fuel (70 MW_{th}) and finally a gasifier in Varkaus using plastic waste as fuel. All mentioned gasifiers are without gas cooler and gas cleaning system. Straw has not been tested as fuel.

The conclusion is, that experience in scaling up and long-time full-scale demonstrations for the following components and processes will be needed:

- Fuel feeding, fuel transport, removal of stone, iron etc. from fuel
- Gas cooling, risk of corrosion and fouling
- Gas cleaning, risk of destroying filter bags, burning of filter bags etc.
- Ash quality. Can the ash be clean enough, low content of C and PAH
- Process risks, start of process, control of process and limitations of explosions

Demonstration of the technique in large scale is still missing and there can be some costly unexpected things, which has to be solved under full-scale conditions and long term running. But the already performed work shows that the process is possible.

8.4 Expected time schedule



8.5 Concluding remarks

The concept of using an atmospheric gasifier with gas cleaning has advantages in being a compact design and very fuel flexible compared to other solutions. Some parts are still very complicated as for example the ash treatment. These complications contribute to the overall price. Long time running experience is unknown and so is the scale factor.

In E2´s production system the economy for the two possible sites at AMV3 and AVV1 is not in the range where the technique is competitive with other solutions. But the demonstration in the 3 MW_{th} gasifier and the design studies have shown, that use of an atmospheric gasifier could be very relevant in countries with other fuel prices and better payment of heat and electricity.

9. APPENDICES

The appendices have been omitted from this version of the report, since they contain some confidential data.
For further information, please contact the Project Co-ordinator, ENERGI E2 (Fax: +45 44806279; E-mail: ebw@e2.dk)