Industrial Biomass Gasification Activities in Sweden 1997-2009

ANNEX 1 to
IEA Biomass Agreement Task 33
Country Report Sweden 2012

Energimyndigheten projekt
IEA Bioenergy Annex 33 – Förgasning av biomassa - 22044-3.

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1. SAMMANFATTNING

Föreliggande rapport utgör ett annex till IEA Biomass Agreement Task 33, Country Report Sweden 2012 och innehåller en sammanfattning av de mycket omfattande svenska utvecklings- och demonstrationsverksamheten inom området termisk förgasning av biobränsle under perioden 1997-2009. Detta material bygger på tidigare Country Reports från den aktuella perioden och innehåller sammanställningar av information som inte längre är så allmänt välkänd, och som kan vara värdefull även i dagsläget för ny och pågående forskning och utveckling på området.

2. SUMMARY

This report is an annex to IEA Biomass Agreement Task 33, Country Report Sweden 2012 and covers a summary of the quite extensive Swedish development and demonstration activities in the field of thermal gasification of biomass and waste in the period 1997-2009. The report is a compilation of previous Country Reports from the period and contains information that is no longer that well-known and that can be of value for currently on-going research and development activities in the field of thermal gasification of biomass.

3. General overview

Commercial development of biomass gasification in Sweden has taken place in different markets during different periods. In the mid. 1970's, influenced by similar development in the USA, a waste gasification plant (Motala Pyrogas) was built. After the second oil crisis, a new process for methanol from biomass "MINO" was developed at pilot scale but not commercialized.

Replacement of oil in existing kilns, e.g. lime kilns and dryers, led to the installation of fixed bed and circulating fluidized bed gasifiers (CFBG). One plant for district heating was also built. As a result of falling oil prices after 1986, no further gasifiers for these applications were built.

During the 1990's, future higher power prices were expected which led to the development of gasifier / gas turbine combined-cycle (BIG-CC), both at pilot plant and semi-commercial scale.

Figure 1 and Table 1 give an overview of existing "commercial" gasifiers in Sweden. Further details on these gasifiers are given below, as well as descriptions of other technologies related to biomass gasification such as waste and black liquor gasification.

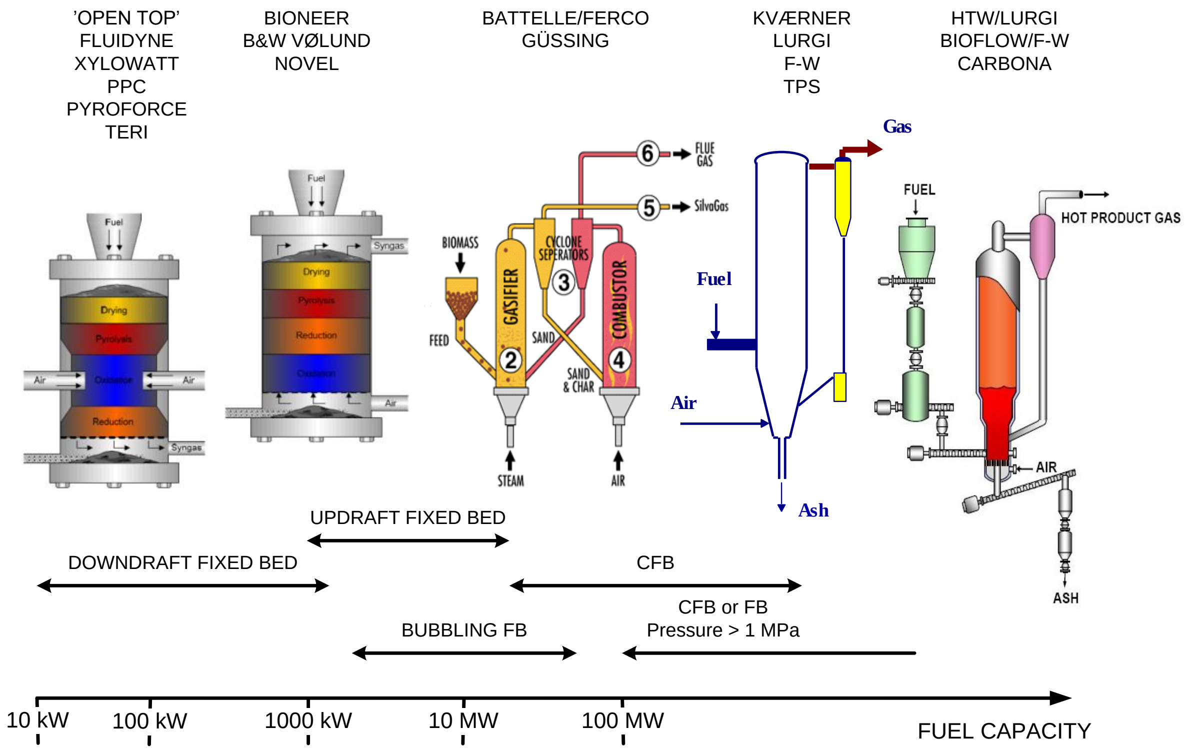

Figure 1 **Commercial biomass gasifiers**

Table 1 Commercial" gasifiers in Sweden (1983-2009)

Process	Location	Type	Size (MWth)	Fuel	Commissioned date	Application	Status
Bioneer	Vilhemina	UD	5	sod peat	1986	boiler	Operating?
Foster Wheeler	Norrsundet	CFB	20	bark / wood chips	1983	lime kiln	operating
Foster Wheeler	Karlsborg	CFB	25	bark / wood chips	1985	lime kiln	n.o.?
Metso (Götaverken)	Värö	CFB	35	bark / wood chips	1987	lime kiln	operating
BIOFLOW (test unit)	Värnamo	PCFB	18	wood chips	1994-96	IGCC	see below
Chemrec (Kværner) (test unit)	Frövifors	EF	4	black liquor	1993	boiler	n.o
Chemrec	Piteå	EF	1	black liquor	2005-	pilot	operating
CHRISGAS	Värnamo	PCFB	18	biomass	2008	Synthesis gas pilot	planned

DD = downdraft reactor
UD = updraft reactor
EF = entrained flow reactor
n.o. = not in operation

3.1 Downdraft gasifiers

Activity in this area has been low in recent years.

3.2 Updraft gasifiers

Three updraft gasifiers have been installed in Sweden. The Finnish "Bioneer" gasifier has, despite some problems, e.g., with feeding and varying gas quality, been running well on both peat and wood chips. The feeder hopper design has been changed in one of the plants. The major emission problem is NO_x from fuels with high nitrogen content such as peat (250-350 mg/MJ). No further units have been sold in Sweden as a result of the low oil prices after 1986.

3.3 CFB gasifiers

The CFB lime kiln gasifiers sold in Sweden were ordered before 1986 when the oil price was high, and ash enrichment in the black liquor recovery cycle was a problem at the pulverized wood combustion lime kiln at ASSI, Piteå, Sweden (now, Smurfit Kappa Kraftliner). Three plants, two from Foster Wheeler and one from Metso (Götaverken) (Table 1), were built.

All the CFB gasifiers suffered from start-up and related problems. Gas leakages and explosions in the feed hopper were the major problems in the Norrsundet gasifier. Sintering problems led to a special design of the lower part of the gasifier with easy access to clean out sinters (Foster Wheeler). Multiple gas use in lime kiln and boiler and "hot dirty gas" valves have been a problem in the Metso (Götaverken) Värö gasifier. Erosion in the valves led to a short valve lifetime. Expansion problems in the hot gas duct were caused by settling of dust which then required unforeseen insulation of the lower part of the duct. Problems in the "hot gas" fired dryer were related to the high dust content partly in the hot flue gas furnace and partly in the flue gas cleaning. The low calorific value gas combustion characteristics "longer and cooler flame" experienced might, depending on the original design of the rotary lime kiln, necessitate the need for oven and / or burner modification. In 2003, this gasifier was operated with enriched air to de-bottleneck the lime kiln in order to increase pulp capacity.

Despite some operational problems, the CFB gasifiers for lime kilns have been in continuous operation for more than fifteen years and have accumulated more operating hours than any other biomass gasifiers in the world.

3.4 Power generation with biomass gasification

Three main routes for power generation from biomass by using gasification have been studied in Sweden:

- Atmospheric gasification coupled to dual fuel engine (3-10 MWe, TPS Termiska Processer AB, TPS)
- Pressurized gasification with hot gas cleaning and IGCC. Either relatively small-scale demonstration (6 MWe, Sydkraft / Foster Wheeler, see below) or large-scale (> 40 MWe, Vattenfall; see below)
- Atmospheric gasification coupled to cold gas cleaning and IGCC at moderate size (10-100 MWe, TPS, see below)

3.5 Waste gasification

Gasification of waste is an interesting option due to the potentially higher yield of electricity, a more stable residue and cheaper gas cleaning as a result of the lower gas volume to be treated.

In ordinary combustion plants, the yield of electricity is limited to approximately 23 % by high-temperature corrosion of the superheaters. Cleaning the gas before combustion could increase the electricity yield in a steam cycle to 28 %, and, if coupled to a gas turbine, could increase the efficiency up to 35-40 %. TPS tested the gas cleaning at pilot plant scale. The test indicated that despite a relatively high tar load in the gas due to the fuel's chlorine content, the bag house filters at about 200°C could be used to recover dust, HCl and mercury. Two TPS CFB gasifiers, without fuel gas cleaning, but integrated with a hot gas combustor and advanced flue gas cleaning, were erected and operated by Ansaldo Aerimpianti close to Florence, Italy (see below).

For hazardous waste, a special plasma supported process "ScanArc" has been developed (see below).

Mälarenergi was planning a waste (SRF quality) gasifier installation with gas cleaning, similar to that Metso is constructing at Lahti. This plan was abandoned in 2010 in favor of a conventional fluidized bed incinerator.

3.6 Black liquor gasification

Tomlinson boilers have been used and developed continuously for more than 100 years in Kraft pulp chemical recovery processes. Their performance is very good in many ways but there are some limitations in the process, such as a fixed ratio between sulfide and sodium in the melt. To increase process flexibility and power output, new process concepts such as black liquor gasification are considered. A future black liquor gasification IGCC system could be combined with bark / chips gasification for a power system with high yield of electricity.

Two different processes have been developed in Sweden. One is from former SKF Plasma Technology and has been developed by Chemrec. The basic idea of the process is to use an entrained flow gasifier at atmospheric pressure for boosting capacity in the soda recovery cycle instead of installing a new large black liquor boiler. A first demonstration plant (4 tonnes/hour dry substance) was erected at the Frövifors Mill in Sweden and was started up in 1992-93 (see later). A pressurized test unit in Karlstad has been operated. There were also plans to erect a new demonstration plant including a gas turbine at Assi, Piteå. A grant for this demonstration plant was awarded by the Swedish State with the plan to start with a research program involving a smaller pilot facility commissioned in 2005, and for which there is also paper and pulp industry co-financing. Further details of the process development are given later.

ABB developed a low temperature CFB gasifier for black liquor in the late 80's. Tests in a small-scale fluidized bed gasifier showed that the carbon content could be reduced to an acceptable level. The fluidized bed has also been shown to work well without any additional fuel except for the black liquor organic. ABB also operated a pilot plant gasifier in Västerås, Sweden, with a fluidized bed reactor under both atmospheric and slightly pressurized conditions. This development is still being pursued by Mälardalens Högskola, Västerås.

3.7 Synthesis gas for liquid fuels and SNG

Following the oil crisis in the 80's, development on synthesis gas from biofuels and peat was initiated. This included development and co-operation with Rheinbraun / UHDE on the HTW process and development of the MINO process.

From 2003, interest in the field of synthesis gas returned and work was initiated on both black liquor and on biomass, focusing on liquid motor fuels.

4. TECHNOLOGY IMPLEMENTATION, PLANTS AND PROJECTS

4.1 Commercial plants before 1990 (not in operation today)

See previous reports for details of these older plants.

4.2 Commercial plants in operation after 1990 or still in operation

In total, three commercial plants based on atmospheric CFB-gasification with a lime kiln have been erected in Sweden, with the pulp industry as gas customer. At least two of these gasifiers are still in operation today, the operating status of the third one at Karlsborg appears to have changed recently and the extent of its operation is not known. Foster Wheeler erected the first unit, proving in practice that by drying the fuel, “flash pyrolysis” and pre-heated air, a rich enough gas could be produced to achieve the desired high temperature in the lime kiln. Other Swedish companies developed similar gasifiers for the same application, e.g. Fläkt / TPS and Kværner.

4.2.1 The Värö plant

The Värö gasifier plant is still in operation and has been described in the main report, IEA Biomass Agreement Task 33, Country Report Sweden 2012.

4.2.2 The TPS / Ansaldo RDF Gasification Process - Grève-in-Chianti plant

TPS started work on the development of an atmospheric-pressure gasification process in the mid-1980s. The initial driving force for the development was the possibility of fuelling lime kiln with biomass-derived gas. Although TPS was successful in developing a CFB gasifier, no commercial units for this particular application were sold. However, TPS licensed their CFB gasifier technology in the late 1980’s to Ansaldo of Italy and provided the design for two RDF-fuelled CFB gasifiers for a commercial plant in Italy (Figure 2). The overall process layout (Figure 3) was designed by Tavolini s.r.l. and built by Ansaldo Aerimpianti. The plant was owned by S.A.F.I. (Servizi Ambientali Area Fiorentina).

<u>Process description</u>

RDF fuel is delivered to the plant in pelletized form. The pellets are fed into the lower sections of the two CFB gasifiers, each of 15 MW fuel capacity. The gasifiers operate at close to atmospheric pressure and at a temperature of approximately 850°C, employing air as the gasification / fluidizing agent. Part of the air is injected into the gasifier vessel through the bottom section, the remainder being injected part way up the vessel. This pattern of air distribution creates a high-density bed in the lower part of the vessel which allows the gasifier to handle relatively large-sized fuel particles. The maximum length of the RDF pellets delivered to the plant is 150 mm (note. TPS stated that its gasifier could operate on non-pelletized RDF fluff and that from the gasification point of view there is no need to pelletize the fuel).

Figure 2 TPS / Ansaldo RDF gasification plant in Grève, Italy

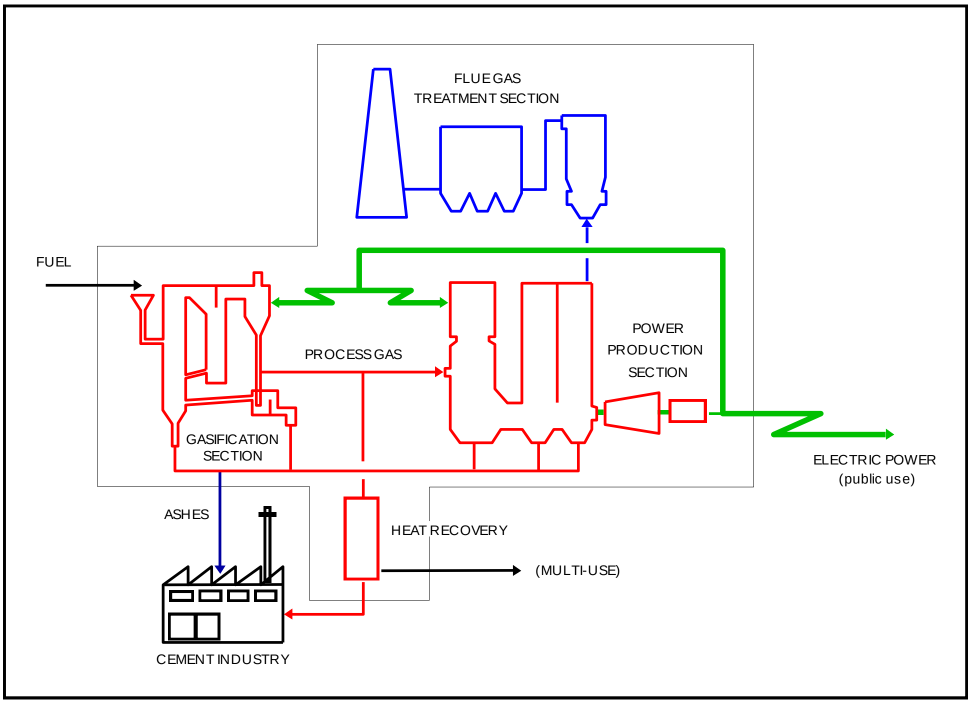

Figure 3 Process scheme of TPS / Ansaldo RDF gasification plant in Grève-in-Chianti

The raw gas from each gasifier passes through two stages of solids separation before being fed to a furnace / boiler. Alternatively, part of this raw gas stream can be led to a nearby cement factory to be used as fuel in the cement kilns. The gas heating value is high, averaging 8 MJ/Nm³. The flue gas exiting the boiler is cleaned in a Research-Cottrell three-stage dry scrubber system before being exhausted through the stack. Steam produced in the boiler drives a 6.7 MWe steam condensing turbine. Due to local restrictions, no flaring of the gas is permitted.

Status

Pilot tests at 2 MW thermal fuel capacity on RDF pellets were carried out at TPS during 1989-90. The Grève plant was turned over to the customer in 1993. Operational problems in the Grève plant were mainly related to combustion of the gas with high dust content. At times, fuel supply to the plant was limiting for the operation of the plant until an RDF pellet production factory was commissioned in 1996.

The original process layout of the plant included a dedicated furnace / boiler and flue gas cleaning system for each of the two gasifiers. Only one such line was installed. In 2003, IEA Bioenergy Task 36 made a comprehensive evaluation of the plant [1].

In 1998, it was planned to modify the plant to include a second combustion line and a product gas cleaning system comprised of a new cyclone solids separator, a high-temperature acid gas / dechlorination unit, a second cyclone solids separator, a gas cooler and ceramic filters. The cost of the modification was estimated at €9.7 million, of which €1.5 million was to be provided through the EU THERMIE program; however this project was not realized.

In the Italian section of the 2004 IEA Task 33 Country Report it was reported that 4 000 and 5 000 tonnes of RDF were processed in the plant during 2000 and 2001, respectively. It appears that the plant was finally closed in 2004; the reason given being that a modern large scale waste-to-energy plant was built in the region.

4.3 Development activities

4.2.3 The VEGA project [2]

In 1990-91, Vattenfall AB and Tampella Power Inc. (today, Metso) made a joint effort through Enviropower to develop a biomass-fuelled IGCC system. This system is based on a simplified IGCC process which applies the gasification technology originally developed by the Institute of Gas Technology (IGT) in Chicago (today, Gas Technology Institute (GTI)), and an advanced hot gas clean-up system. Enviropower's gasification pilot plant of 15 MW thermal input (80 tonne per day on biomass) in Tampere, Finland, was used for research, development and component testing of the gasification and gas clean-up process. Gas turbine combustion tests, using low BTU gas, were carried out at General Electric Power Generation Development Laboratory in Schenectady, USA. Biomass fuel drying tests were performed at commercial facilities of different dryer manufacturers. A novel fuel feeding system was developed and tested by Vattenfall for the direct feeding to pressurized systems of mainly biomass type fuels.

Full-scale demonstration plants in Sweden and Finland were studied but were not realized due to high cost and low electric price. Vattenfall withdrew from the co-operation and later on Kværner bought Tampella Power. A special arrangement gave Carbona Oy the rights to utilize and commercialize the technology. Carbona was later taken over by Andritz.

4.2.4 The BIOFLOW (Sydkraft / Foster Wheeler) concept in Värnamo

Sydkraft AB (today, E.ON Sweden) built the world's first complete IGCC power plant which uses wood as fuel (Figure 4). The plant is located at Värnamo, Sweden, and the technology used is based on gasification in a pressurized CFB. The gasification technology was developed in co-operation between Sydkraft and Foster Wheeler Energy International Inc. The plant can be operated as a co-generation plant and is cooled by a district heating system or by separate air coolers. The air coolers were installed so that the plant could be operated independently of the heat load while test runs were being performed.

Figure 4 **World's first complete IGCC power plant at Värnamo**

The plant (6 MWe / 9 MWth) was constructed during 1991-1993, operated 1993-1999 and was an important step forward in developing highly efficient and environmentally acceptable technologies based on biomass. The aim of the project was to demonstrate the complete integration of a gasification plant and a combined-cycle plant, fuelled by biomass. The idea was to demonstrate the technology rather than to run a fully optimized plant. Flexible and conservative solutions were chosen for the plant layout and design to ensure the success of the project and to make the plant suitable for RD&D activities. The accumulated operating experience at the plant as per 1999 was about 8 500 hours of gasification runs of which 3 600 hours of operation was as a fully integrated plant. The test runs were successful and the plant was operated on different wood fuels as well as straw and refuse-derived fuel (RDF).

The demonstration program was concluded in 2000 and the plant was mothballed as it was not economical to operate given the commercial conditions prevailing in Sweden at the time. Significant efforts were made however to make use of this plant as a research facility and for this purpose a new company Växjö Värnamo Biomass Gasification Centre (VVBGC) was established, see below.

A detailed summary report of the demonstration program has been published in Swedish and English [3, 4].

Process description

A simplified process diagram, showing the components of the gasification plant, is shown in Figure 5 and Figure 6, and some data given in Table 2.

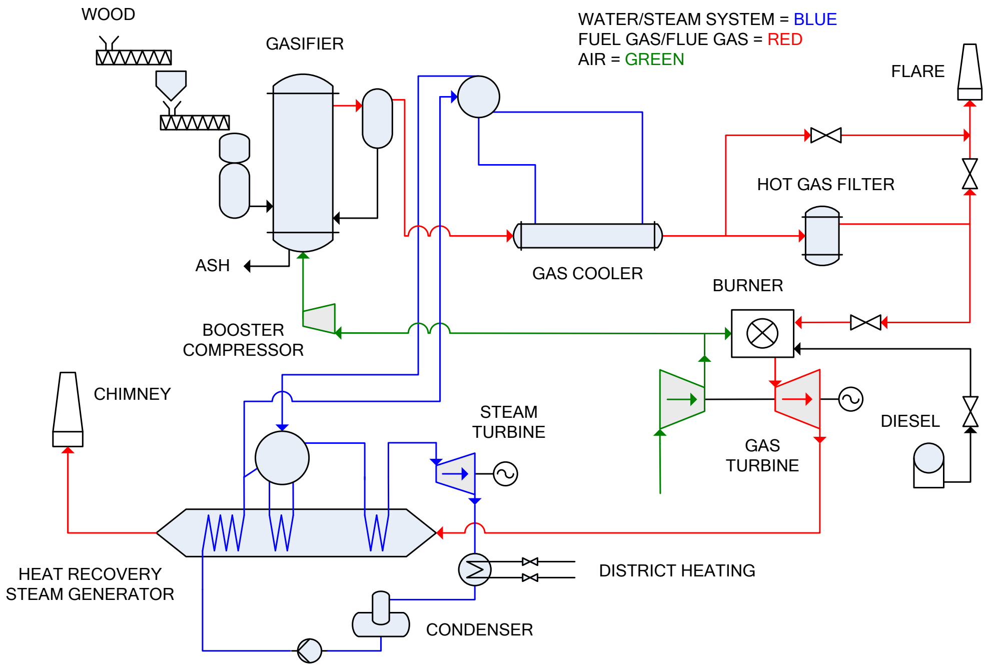

Figure 5 Process diagram of Värnamo plant

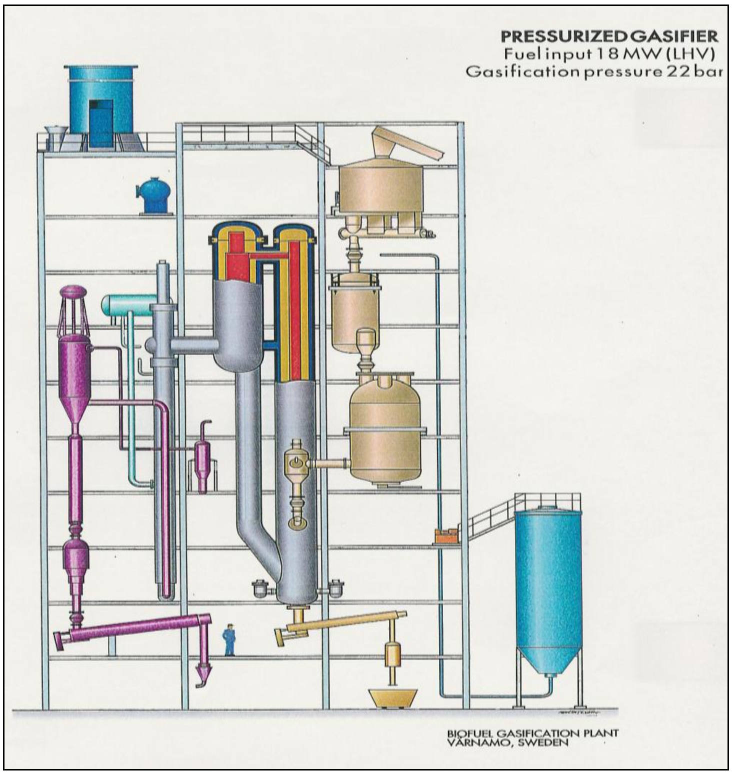

Figure 6 **Cross section of the Värnamo gasification plant**

Table 2 **Technical data of the Värnamo plant**

Power / heat generation	6 MWe / 9 MWth
Fuel input	18 MW fuel (85 % dry substance)
Fuel	Wood chips (Several other fuels have been tested with good results)
Net electrical efficiency (LCV basis)	32 %
Total net efficiency (LCV basis)	83 %
Gasification pressure / temperature	18 bar.g / 950ºC
Lower calorific value of product gas	5 MJ/m^{3}n
Steam pressure / temperature	40 bar.a / 455ºC

The dried and crushed wood fuel is pressurized in a lock hopper system to a level determined by the pressure ratio of the gas turbine, and fed by screw feeders into the gasifier a few meters above the bottom. The operating temperature of the gasifier is 950-1 000°C and the pressure is approximately 18 bar.g. The gasifier is a CFB and consists of the gasifier itself, cyclone and cyclone return leg, all of which are fully refractory-lined.

The gasifier is air-blown. About 10 % of the air in the gas turbine compressor is extracted, further compressed in a booster compressor, and then injected into the bottom of the gasifier.

The fuel is dried, pyrolyzed and gasified on entering the gasifier. The gas produced transports the bed material and the remaining char to the top of the gasifier and into the cyclone. In the cyclone, most of the solids are separated from the gas and are returned to the bottom of the gasifier through the return leg. The recirculated solids contain some char which is burned in the bottom zone where air is introduced into the gasifier. Combustion of the fuel and gas maintains the required temperature in the gasifier.

Downstream of the cyclone, the gas produced flows to a gas cooler and a hot gas filter. The gas cooler is of a fire tube design and cools the gas to 350-400°C. After cooling, the gas enters the candle filter vessel where particulate clean-up occurs. Ash is discharged from the candle filter, as well as from the bottom of the gasifier, and is cooled and depressurized.

The gas produced is burned in the combustion chambers and expands through the gas turbine, generating 4.2 MW of electricity. The gas turbine is a single-shaft industrial unit. The fuel supply system, fuel injectors and the combustors were redesigned to suit the low calorific value gas (5 MJ/m^3).

The hot flue gas from the gas turbine is fed to the heat recovery steam generator (HRSG), where the steam generated, along with steam from the gas cooler, is superheated and then supplied to a steam turbine (40 bar, 455°C), generating 1.8 MWe.

The plant is equipped with a flare on the roof of the gasification building. This is used during start-up and to protect the gas turbine when testing under uncertain conditions.

An extensive demonstration / development program was carried out during 1996-2000. Parts of the work was performed in collaboration between Sydkraft, Foster Wheeler, Electricité de France and Elkraft. The overall aim of the program was to verify the status and future potential of the biomass IGCC concept from both a technical and economic point of view. In order to achieve this it was important to identify and verify the status of different parameters, e.g. operability, maintainability and availability. Of particular interest to the success of the gasification technology was verification of the quality of the gas produced in the gasifier, as well as operation of the gas turbine.

Experience gained during test operation

The first gas was generated at low pressure in June 1993.

Tests with different bed materials, temperatures and pressure levels, caused deposits to occur at times. During the tests with limestone and dolomite as bed material, recarbonisation of the limestone / dolomite resulted in deposits in the gas cooling system which in turn provided insufficient cracking of high molecular by-products, which caused fouling on the cooler tubes. The use of magnesite (MgO) as bed material in the gasifier proved to be very successful. As magnesite is more expensive than dolomite, tests were carried out to check the feasibility of recirculating bottom ash, and thus reuse the magnesite drained from the system, these tests proved to be successful. Whilst it was concluded that significant deposits can be handled with a suitable design of gasifier and downstream components, it is still believed that it would be useful to continue testing different bed materials or mixtures of bed materials to further optimize the gasification process, i.e. achieve minimum of deposits, cost and best possible gas quality.

Gas quality

During the commissioning as well as during the demonstration program the gas quality was checked regularly. The hydrogen content in the gas turned out to be slightly lower than predicted, but the heating value was maintained as a result of an increase in methane. A typical range of dry gas composition is shown in Table 3. Gas heating values in the range 5.0-6.3 MJ/m³n were recorded.

Table 3 Typical ranges of dry gas composition in the Värnamo plant (% vol.)

CO	H_2	CH_4	CO_2	N_2
16-19 %	9.5-12 %	5.8-7.5 %	14.4-17.5 %	48-52 %

Different operating conditions in the gasifier as well as a change of fuel produced different amounts of light tars and benzene, as can be seen in Table 4. Bark tends to produce less benzene and tars than ordinary wood chips.

Table 4 Light tars and benzene content in product gas in the Värnamo plant (mg/m³n)

Fuel	Benzene	Light tars
Bark 60 % and forest residues 40 %	5 000 - 6 300	1 500 - 2 200
Pine chips	7 000 - 9 000	2 500 - 3 700

Due to the relatively low combustion temperatures in the gas turbine combustors when burning product gas, thermal NOx was very low. Total NOx emissions could however be higher than on gas turbine operation on liquid fuel with steam injection due to the conversion of fuel bound nitrogen, mainly ammonia, into NOx. The recorded levels of alkalis were below 0.1 ppm wt.

Hot gas filter performance

The principle behind the hot gas filtration system is to allow gaseous tars to pass through the filter and other tars to stick to the filter cake and not pass into the fine pore structure of the filter itself. Originally, a ceramic hot gas filter was installed. The ceramic filter showed good filtration efficiency, with stable pressure drop. However, after more than 1 200 hours of trouble free operation, two ceramic candles suddenly broke. The complete set of candles was changed to a new design of ceramic candles. After less than 350 operating hours, one of the new types of candles broke. The breakdown was determined by the supplier to be caused by mechanical fatigue since micro cracking was found in all elements tested.

During summer 1998, it was decided to install metal filter candles in the main hot gas filter instead of the ceramic candles. The metal filter candles were installed in the original filter vessel but with a new tube sheet and back-pulsing arrangement. The metal filter, like the ceramics, showed very good filtration efficiency, with stable pressure drop. This filter has been in operation for more than 2 500 hours without any filter breakage or other damage during operation. Investigations carried out after the end of the last test indicated that there was no degradation of the elements although they had been exposed to gas and ash not only from wood chips but also from RDF and straw.

Gas turbine experience

The gas turbine installed in the plant is a near-standard Typhoon from ABB Alstom Gas Turbines in Lincoln, England (now Siemens Industrial Turbines). Modified components are the combustors, the burners and the addition of an air bleed from the compressor. A special design gas control module was also developed to control the product gas, steam and nitrogen to the unit.

Prior to being supplied to Värnamo, the special combustors and burners were tested in a rig in England utilizing synthetic gas. Combustion was always reliable in the turbine whether operating on gas fuel or liquid. The relatively low heating value of the gas (about 1/10th of natural gas) caused no problem for the gas turbine and a stable flame was always maintained even when the heating value was lower than normal. Not even during earlier operation at the Värnamo plant was it necessary to maintain a pilot flame of liquid fuel and thus operation during all 3 600 hours as a fully integrated plant was on 100 % gas for the LCV gas from 40 % to full operating load.

Complete combustion of the hydrocarbons was always achieved with emissions between 1 and 4 ppm only, whereas a slightly high figure of CO was observed with figures up to and sometimes even above 200 ppm on part load operation. As mentioned before, levels of NOx around 150 ppm were recorded when operating on gas produced from biomass with high nitrogen content (such as bark), whilst the lower nitrogen content of hardwood considerably reduces the NOx, down to as little as 50 ppm.

During commissioning and the first years of testing, forest residue and wood chips were the fuels generally used. However, a variety of fuels were tested in the plant during the demonstration program, such as wood chips, forest residue (bark, branches, etc.), sawdust and bark pellets, willow (salix), straw and RDF.

All these fuels proved to be easy to gasify without causing deposits or sinters in the systems. Bark proved to be an excellent fuel and was easily gasified with the gas being suitable for filtration and gas turbine operation. The high levels of alkalis in willow (salix) did not cause any problems and the amount of sintered / agglomerated material in the bottom ash was very small.

Straw has always been considered a very difficult fuel to burn / gasify due to its high levels of alkaline and large amount of ash in the fuel. Also, the chlorine level is very high in comparison to wood fuels. Tests were carried out with straw mixed with bark, and with 100 % straw. About 200 tonnes of straw were gasified without any problems or sintering, and a gas was produced with a hydrogen content slightly higher than normal, which proved to be excellent for gas turbine operation.

Encouraging results were achieved in the tests on RDF, including gas turbine operation on the gas produced.

<u>Conclusions from the demonstration program</u>

The difficulties encountered initially in the Värnamo project were overcome after a couple of years of intense commissioning and testing.

The Demonstration Program, started up during 1996, was very successful and proved that pressurized biomass IGCC technology works. The complete plant was in operation in excess of 3 600 hours with the gas turbine operating solely on product gas produced by the gasifier. Huge experience was gained from more than 8 500 hours gasifier operation. Results achieved can be summarized as follows:

- High pressure gasification technology works
- Gas produced can be burnt in a gas turbine under stable conditions
- Hot gas filtration is efficient and reliable
- Technology is capable of gasifying “difficult fuels”
- No harmful effects identified on gas turbine or other components
- NOx emission slightly high at present for some fuels, but solutions available
- Emissions of HC very low and emissions of dioxins even for chlorine-rich fuels below detection level
- The biomass gasification technology is very suitable for retrofit to existing natural gas-fired combined-cycle (NGCC) plants

The market potential for the pressurized gasification technology developed at Värnamo can be summarized as follows:

- Industrial back-pressure CHP generation plants, such as for process steam in the pulp and paper industry, will have the highest competitiveness
- The high fuel flexibility shown opens the way for building plants for more difficult fuels such as straw, RDF and bagasse
- An interesting application may be to supplement a NGCC plant with a gasification plant, so that part of the natural gas flow can be replaced by product gas
- The competitiveness compared to conventional biomass-fired condensing power plants is promising
- In the short-term perspective, the market will be dependent on political measures for reducing CO_2 emissions

From 2000 efforts were made to create new partnerships to maintain and utilize the Värnamo plant. In 2003, applications were made by several consortia to the EC for financial support for projects aimed at generating a hydrogen-rich gas that can be upgraded to commercial quality hydrogen or a synthesis gas, or for producing methanol, hydrogen, ammonia and DME or Fischer-Tropsch diesel from renewable fuels. One application that was successful was the CHRISGAS project.

4.2.5 The CHRISGAS project [www.chrisgas.com]

Background

In 2003, an application to DG Research for part funding of the CHRISGAS project was successful. The project is aimed at establishing the necessary design basis for each process step, including test work in the Värnamo plant. The project started on 1st September 2004 and pilot plant tests were planned for 2006.

In order to guarantee the availability of the Värnamo plant by public funding after it was mothballed by Sydkraft, a non-profit project-based company was established at Värnamo by Växjö Energi AB and Värnamo Energi AB, both local publicly-owned energy companies, on behalf of Växjö University. This company, named Växjö Värnamo Biomass Gasification Centre (VVBGC) was incorporated in December 2003. The plant and associated IPR were taken over from the previous plant owner in 2004. This arrangement safeguarded access to and availability of the plant, including the use of qualified operating staff. In December 2004, the contract for the CHRISGAS project was signed and the project started, continuing through to 2009. The project was to use the Värnamo plant for oxygen-blown gasification to generate synthesis gas from biomass.

CHRISGAS objectives and structure

The primary objective of the CHRISGAS project was to demonstrate, in the Värnamo plant, the manufacture of a hydrogen-rich gas from a renewable feedstock, i.e. biomass. The demonstration part of the project consisted of a number of tasks for which the objectives were:

- Conversion of several solid biomasses into a medium calorific value gas by gasification at elevated pressure using a steam and oxygen mixture
- Cleaning of the generated gas from particulates in a high temperature filter. Note that hot gas cleaning is advantageous for the overall energy balance when a reformer is applied directly after the cleaning section because reforming requires a high inlet temperature
- Purification of the generated gas by catalytic autothermal steam reforming of not only tars, but of methane and other light hydrocarbons, to generate a raw synthesis gas consisting mainly of carbon monoxide and hydrogen as energy carriers

In order to provide a sound technical background to the process to be installed at Värnamo, a supporting R&D program on various technical aspects of the proposed process was conducted, the objectives of which included:

- Studies of the conditioning of the hydrogen-rich raw synthesis gas to the quality stipulated for synthesis gas suitable for manufacture of DME or other potential products
- Studies of the production of these fuels from various biomasses, at the scale and cost representative of typical biomass fuel chains in various regions in Europe
- Development of a feed system based on a piston feeder. The advantages of piston feeding are that the total energy consumption is much lower than that of lock hoppers, the feeder is more compact and the capacity of one feeder can be very large

During 2005 and 2006, planning of the modification of the plant for the CHRISGAS project was made, and an application to STEM for the balance of funding required for the program was submitted. In September 2006, following the application for financial support in May 2006, an international expert evaluation of the project was made. STEM evaluated this application favorably, but as a result budgetary restrictions and of the STEM policy changes, 75 % of the funding was allocated conditional on the establishment of an industrial stakeholder group being formed to give stronger industrial thrust to the project and to provide the balance of financing.

<u>Activities in the plant prior to the rebuild</u>

The plant was mothballed in 2000. Actions taken in 2004, apart from building a new site organization, was to make a status review of the existing facilities. This review concluded that although, in general, the active mothballing scheme had prevented the plant from suffering any extensive deterioration, some localized damage had occurred from e.g. freezing or corrosion, and furthermore, all wear in the plant on valves, etc. up to its shut-down in 1999, remained of course and instrumentation had suffered from age and other factors. During the end of 2005 and the first half of 2006, all the mechanical repairs were made, the vessel and other parts inspected and the turbines serviced.

One part of the plant that had been discussed during the planning stage was the control system which was installed in 1992. After assessing the new needs and the availability of spare parts, it was decided to install a new system. An ABB Freelance system was installed by September 2006, incorporating all the signals, sequences, interlocks, etc. from the old system. Figure 7 shows a process screen print from the new control system, showing the gas turbine in operation on low load.

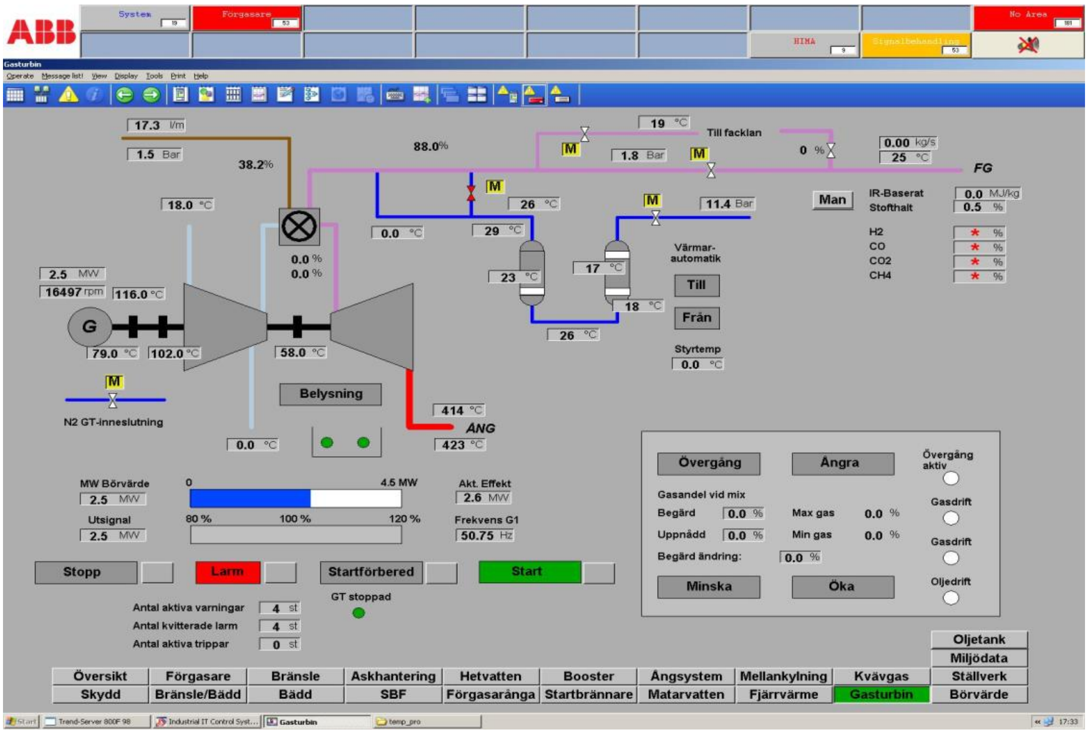

Figure 7 A process screen showing the gas turbine from the new DCS system

Following the successful implementation of the control system, the plant was re-commissioned for operation in the present configuration. The reason for this re-commissioning, in spite of the forthcoming plant rebuild, was to check the control system installation, as e.g. the feeder sequences would still be used in the rebuilt plant, and the chance to provide hands-on training for the new operating crew. In October 2006, the combined cycle was operated on diesel oil for approximately 100 hours, generating power to the grid, where air could also be extracted for the gasification system to allow heating up and pressure testing under hot conditions. In March 2007, a new test, also including feeding fuel and firing biomass at limited pressure for a limited period, was carried out. In September 2007, for the first time since 1999, gasification mode operation was achieved for a day at full capacity and pressure without integration with the gas turbine, Figure 8. Gas analyses were taken and KTH was involved in measuring the tar by a novel method, going further than the SPA method.

Figure 8 Flaring of product gas in September 2007

Proposed modifications to the plant

On the rebuild and modification side, engineering work was initiated in 2005. In 2005, conceptual engineering of the plant was made, identifying limiting operating conditions, interface problems between new and old equipment and giving an outline flow sheet. In the end of 2005 and early 2006, a basic engineering study was made by some of the Swedish CHRISGAS partners, with support from Carl Bro (today, Grontmij Sweden), a Swedish engineering company. This resulted in a number of files containing PID's, material lists, etc., which were the basis for the budget estimate for the cost of the rebuild of 182 million SEK, and the commissioning and operating cost amounting to 108 million SEK. The application to STEM for financing was based on this work. In early 2007, a contract for detailed engineering was awarded to Sweco PIC, but lack of funding prevented good progress.

The proposed modifications to the Värnamo plant are shown in Figure 9.

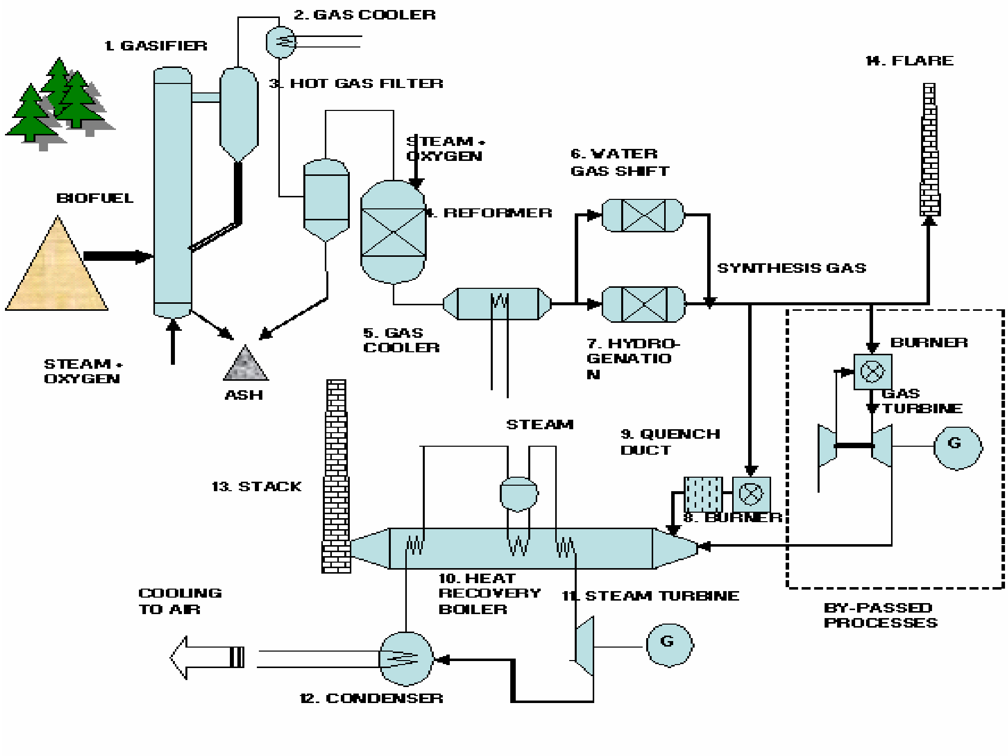

Figure 9 The Värnamo plant after the modifications

The most important changes proposed were:

- The gasifier is blown with pressurized oxygen and steam
- A new hot gas filter is positioned directly downstream of the cyclone, and is therefore exposed to a much higher temperature than the previous hot gas filter
- A combined catalytic or thermal high temperature reformer is installed
- A water gas shift system is added after reforming and gas cooling[1]

The hydrogen-rich gas can, by means of more or less conventional processing, be upgraded to commercial quality hydrogen or a synthesis gas suitable for the production of liquid fuels. These include a system for the removal of acid gases, notably CO_2 from the raw synthesis gas, followed by compression of the gas to the level of synthesis processes of interest, i.e. 60-100 bar. Such process steps were to be studied with the purpose of installing also the downstream upgrading and gas cleaning units at Värnamo at a later date (as an extension of the CHRISGAS project).

After completion of case studies, it is likely that three fuel production routes would be considered for the follow-up project, i.e.:

[1] Note. The gas turbine is still in place as VVBGC intends to maintain the capacity to engage in IGCC projects. Assuming that development of a new piston feeding system is successful, and that the feeder prototype is suitable for installation at Värnamo, it may also be installed and demonstrated.

- Hydrogen
- DME / methanol process
- Fischer-Tropsch synthesis

4.2.6 The TPS gasification and hot gas cleaning process - incl. ARBRE plant

TPS R&D

TPS was a privately-owned research, development and design company (from 2003-2007 part of the Talloil group, from 2007 part of ACAP Invest AB) working in the field of energy technology. The company ceased its operation in 2010. The company offered product and services and performed research and development on gasification and combustion. The research was based mainly on experiments in the laboratory and on computerized flow simulation. Commercial exploitation of the new techniques developed by the company was typically achieved through technology licensing and joint venture activities. Research and development projects of TPS were often funded on a contract basis by STEM, the EU and by private companies.

TPS was the designated technology supplier for the Grève-in-Chianti project in Italy, the Brazilian BIG-GT project and the ARBRE project, all of which have been described earlier. TPS was also a partner in the Framework 6 CHRISGAS project.

TPS's R&D work on biomass gasification began in the late 1970's. During the early 1980's, the work concentrated on the development of the MINO process for gasification of wood and peat to synthesis gas. This oxygen-blown process featured a high temperature filter and a catalytic gas cleaning step; a pilot plant of 2.5 MW capacity was operated at up to 28 bar. During the latter part of the 1980's, research and pilot plant test work concentrated on the air-blown atmospheric-pressure CFB gasification process and its application to the thermal processing of biomass and waste fuels, featuring a patented gas cleaning step. TPS had a 2 MW atmospheric-pressure gasification pilot plant on its premises, including a CFB gasifier, CFB tar cracker, filter, wet scrubber and diesel engine, up to the company's relocation in 2006.

A small fluidized bed gasifier, i.e. a fuel input of 20-50 kWth, was installed at TPS in the mid. 1990's. In this gasifier a realistic gas was produced. Since the gasifier had external electric heating (approx. 10 kW) it was possible to achieve calorific values of the gas corresponding to that normally found in commercial scale equipment (5–6 MJ/m^3 dry gas). The gasifier system was equipped with a cyclone and a heated ceramic filter for removal of particulates. This gasifier was installed at KTH in 2010, see the main Country Report 2012.

A flexible pressurized apparatus, operating at up to 30 bar, was also designed and installed in the mid 1990's. The purpose of this apparatus was to perform investigations of high temperature gas cleaning by means of thermal, catalytic or chemical processes. A semi-continuous fuel feeding concept, at a maximum rate of 700 g/h, allowed constant formation of a gas product at 700°C. The gas product, or gas from another external source, e.g. gas bottles, was subsequently introduced into a fixed bed secondary reactor where gas clean-up or reforming took place. This unit was demolished when TPS moved from the Studsvik area.

Scale-up and industrial applications

In the view of TPS, there are three main applications for cold tar-free biomass-derived gas for electricity production:

1. Firing of the gas in a furnace / boiler without further flue gas cleaning (Figure 10)
2. Firing of the gas in a gas engine / dual-fuel engine
3. Firing of the gas in an IGCC system (Figure 11)

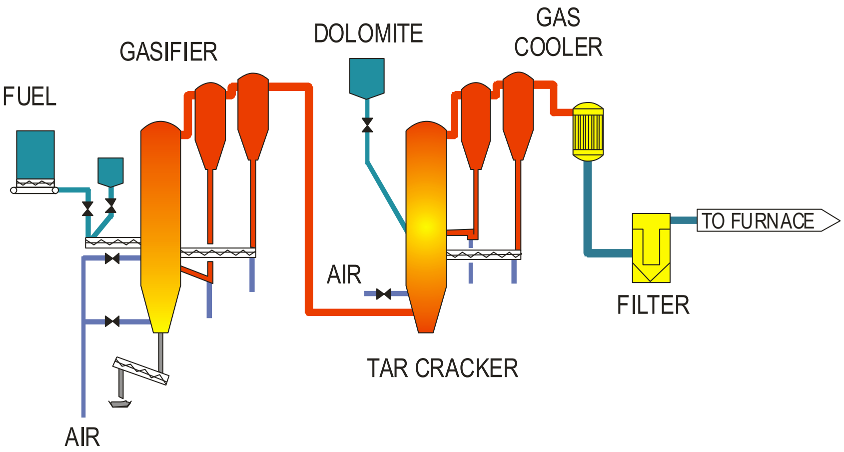

Figure 10 TPS gasification and gas cleaning process scheme

The TPS process is described in detail later in the section on the IGCC plant installed in Yorkshire, England (i.e. the so-called ARBRE plant).

During the latter part of the 1980's, TPS worked on the development of a hot gas cleaning process for application to biomass and waste-derived gases based on the use of dolomite as a tar cracking catalyst and absorbent for chloride. In 1987, the existing 2 MW CFB gasifier at TPS was extended through the construction of a catalytic tar cracker, gas quench and cold gas cleaning equipment, as well as by a 0.5 MW shaft power turbo-charged eight cylinder diesel engine.

This hot gas cleaning technology was first demonstrated over long operational periods at pilot scale in the late 1980's, the gas being fired successfully in the dual-fuel engine. The engine was run for more than 700 hours with the expected efficiency, but yielded an exhaust gas with a relatively high concentration of carbon monoxide and hydrocarbons in comparison to combustion boilers. At that time, it was thought that a sizeable market existed in Sweden for the commercial application of TPS's gasification / hot gas cleaning technology to small-scale electricity production plants (say 5 to 20 MWe). Although TPS did not succeed in selling any small-scale plants based on this gasification / hot gas cleaning technology, TPS continued to develop this application for IGCC systems and were successful in having its technology selected for several important projects aimed at proving the technical and commercial viability of biomass-fuelled IGCC systems (see below).

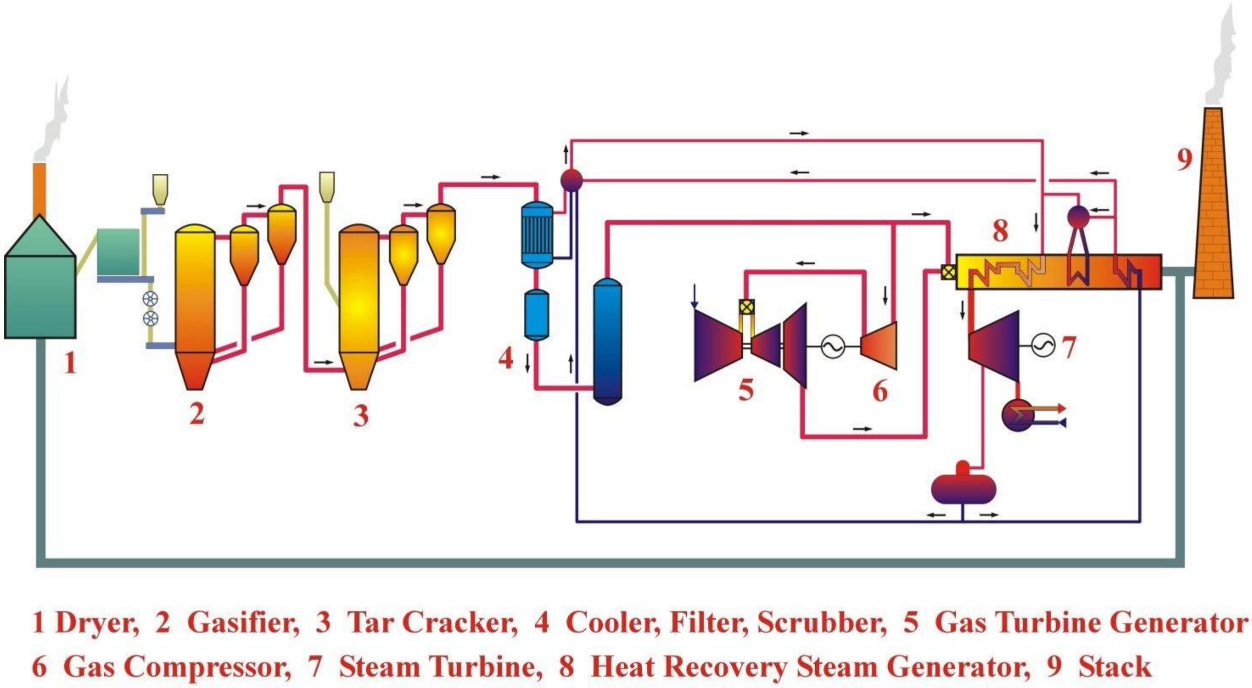

Figure 11 TPS CFBG integrated gasification combined-cycle process scheme

The main advantage with gasification / dual-fuel engine is that a high yield of electricity can be achieved in small-scale systems (i.e. 30 % efficiency at 3-10 MWe). No commercial or demonstration plants have yet been built.

As a part of the Brazilian project (see below), the TPS pilot plant was operated during ten separate one-week tests. In April 1997, the gasifier and cracker were operated continuously for four weeks with an availability higher than 90 %. Further tests were carried out on RDF and on sugar cane bagasse and trash, and mixtures of these two fuels up to 2002. In 2006, when TPS relocated its offices, the pilot plant was demolished.

Projects and studies

In 1992, TPS was awarded a contract to further develop gasification technology for application in a 30 MWe eucalyptus-fuelled IGCC plant to be built in North-eastern Brazil. The development work was sponsored by, amongst others, the World Bank and the Swedish National Board for Industrial and Technical Development (NUTEK), and after 2000 also by the EC.

In 1995, the gasification development work was successfully completed and after an evaluation of this technology and a competing pressurized gasification technology proposed by Bioflow based on their experience from the Värnamo plant, TPS's technology was selected for use in the proposed plant. The General Electric LM 2500 gas turbine, which was to be modified to accommodate the product gas from the gasifier, was also selected for use.

A consortium for carrying out the project, SER, Sistemas de Energi Renovavel, comprising Shell Brasil, Eletrobrás and CHESF, was established but never became fully operative. With time, company policies and perspectives changed and partners withdrew from the project. In early 2004, a private company in Brazil interested in pursuing the project approached the World Bank for its approval of this new arrangement, but the effort failed and the project terminated in 2004.

A similar project study in the Netherlands for UNA, the North Holland project was conducted in the period 1993-1996 in cooperation with the Schelde group. The plant was a similar size to that of the Brazilian plant and was meant to operate on a variety of waste biomass. Again, the financing support failed and the project was terminated. TPS also made a bid for the AMERGAS gasification plant together with Schelde, but the contract was awarded to Lurgi.

Sugar cane bagasse

Apart from woody biomass, a huge potential for power generation from waste fuels exists within the sugar cane industry. 1 200 million tonnes of sugar cane is harvested annually, which corresponds to a worldwide electricity production potential of 40 000 MW or 300 TWh/year in the eighty countries where sugar cane is grown on a significant basis.

Project BRA/96/G31 - "Biomass Power Generation: Sugar Cane Bagasse and Trash" was initiated in 1997 to evaluate and develop the technology required in the complete fuel-to-electricity chain; starting with cultivation and recovery of sugar cane by-product fuels to electric power generation with advanced systems (i.e. BIG-GT) integrated with a sugar mill. The first phase of the project was organized as an extension of the eucalyptus-based Brazilian BIG-GT project, financed roughly equally between Copersucar and GEF, through UNDP. In 2000, additional support for an extension of the work was received from the EU ENERGIE program and STEM as part of the EU-BR-IDGE project.

Pilot plant tests on bagasse pellets were performed under two contracts, during 1998 and 1999, and the success of these tests led to an extension of the project, this extension also being a part of the EU-BR-IDGE project, which was to include test work on loose sugar cane trash, completed in 2001. On the basis of these tests, conceptual engineering of a bagasse and cane trash-fuelled combined-cycle power plant integrated with a typical sugar mill in Brazil was performed. However, plans to establish a demonstration project in a sugar mill in Brazil, or in Cuba through another project, failed.

1.1.6.1 Project ARBRE [5]

In 1993, the EU agreed to part-finance the construction of at least two short rotation coppice-fuelled combined-cycle plants in Europe, each of 8 to 12 MWe capacity, including Project ARBRE in the UK. Figure 12 shows a simplified process flow diagram of the plant.

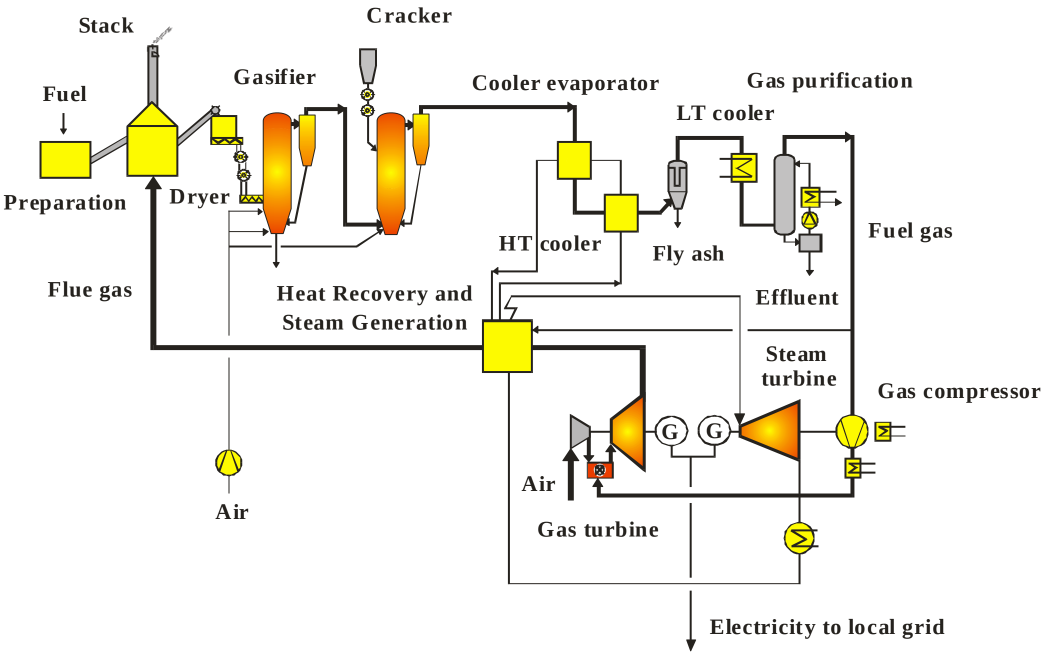

Figure 12 ARBRE plant process scheme

In December 1994, the proposed generating plant became the recipient of an UK NFFO3 (Non-Fossil Fuel Obligation, 3rd tranche) contract providing an index-linked price of 8.75 p per kWh (1993, linked to the UK retail price index) guaranteed until 2013.

In December 1995, ARBRE Energy Limited (AEL), the majority owner being Yorkshire Water plc, later to be renamed Kelda plc, was formed to implement the generating plant based on the following understanding of the role of AEL:

- to contract with local farmers to cultivate, harvest and transport short rotation coppice (SRC) to the generating plant
- to contract with reputable fuel suppliers to deliver forestry residues to the generating plant
- to award a turnkey contract for design, construction, commissioning and performance testing of the IGCC plant
- to award a 15 year O&M contract to a third party

In the preparatory work for the RFP documentation, several important technical decisions were made, including:

- based on its proven use in similar applications, the Typhoon gas turbine (today SGT 100) from Siemens would be used
- the plant would have a significant amount of supplementary firing in order to achieve the desired 8 MWe output
- the feedstock to the plant would be dried with the waste heat in the flue gas from the gas turbine
- the process design of the gasification plant would be supplied by TPS through a sub-contract to the turnkey contractor

The ARBRE plant is an IGCC plant comprised of the following major components:

- wood delivery, weighing, reception / storage, drying and feeding
- TPS atmospheric-pressure gasifier, including air supply
- TPS hot gas conditioning vessel (so-called “tar cracker”)
- fuel gas cooling
- fuel gas cold cleaning (i.e. bag filter and wet scrubber)
- fuel gas compressor
- “Typhoon” gas turbine
- waste heat boiler
- steam turbine

The plant was to consume 43 000 dry tonnes of wood per year and its net electrical efficiency was projected to be ca. 30 %. This relatively low efficiency was a result of the requirement of eligibility for the EU grant that net generation must reach 8 MWe, which after selecting the technically proven Typhoon gas turbine of 4.5 MW could only be achieved by increasing the contribution of the steam turbine cycle to the overall output by firing a third of the gas produced directly into the HRSG, thereby bypassing the gas turbine. Thus, the plant configuration was not an example of a typical generic combined cycle.

Following the submission of an Environmental Statement in May 1996 and widespread consultation with the local planning authority, local residents, the UK Department of Energy and many other organizations, planning permission for the project was granted in February 1997.

During 1996, the RFP documentation was issued and several companies submitted preliminary offers. During 1996 and early 1997, detailed discussions took place with two companies and in September 1997, a conditional turnkey contract, valued at ca. £23 million, was awarded to Schelde Engineers & Contractors BV, the Netherlands. At that time, the planned start-up date for the plant was early 2000. McLellan and Partners, UK was appointed as consulting engineer to the project and was responsible for managing the turnkey contract.

In April 1998, and only after the plans for project financing had been abandoned and replaced by majority financing by Kelda, could the turnkey contract be made unconditional. At the same time, SEC signed the gasification process design sub-contract with TPS. The plant's O&M contract was awarded by AEL to Schelde Heat and Power (SHP) UK Limited.

Fuel supply, preparation and feeding

The wood is delivered in chipped form to the plant by truck. The fuel supply, preparation and feeding system consists of a weigh-bridge, a reception pit, an A-frame storage building (providing three days bulk storage), a dryer (which dries the fuel to around 10 % moisture content with flue gases leaving the waste heat boiler) plus travelling screws, screws and elevator and conveyors interconnecting these latter three units and also leading to the two gasifier fuel feed silos.

Gas generation and tar cracking

The wood is fed to a TPS air-blown CFB gasifier operating at around 850°C and close to atmospheric pressure, and converted into a low calorific value gas.

The gas produced in the gasifier is cleansed of tars in a tar cracker; a second CFB operating at a slightly higher temperature. By catalytically cracking the tar to simpler compounds in this vessel, the gas can be cleansed of particulates and alkalis in downstream conventional gas cleaning equipment. In addition, this catalytic process means that there is no significant reduction in the chemical heating value of the gas, as would be the case if the tar was thermally cracked at higher temperature.

Gas cooling, cleaning and compression

After leaving the tar cracker, the gas is cooled before passing through bag filters at 200°C to remove fine particulates (fly ash, alkalis condensed on fly ash and chloride as $CaCl_2$). The gas is then cooled further before the final cleaning stage. The heat removed during the gas cooling stages is recycled for boiler feedwater pre-heating and steam raising. The final cleaning stage is a wet scrubbing procedure to condense out any remaining tars and water vapor and remove traces of alkali metals, as well as to remove ammonia using a dilute sulfuric acid solution.

Power plant

The clean gas resulting is then split into two streams and fed to the combined-cycle generating plant.

The main gas stream is compressed and fed to a Typhoon gas turbine with a rated output of 4.75 MW. The hot gas turbine exhaust gases then pass to a boiler for heat recovery and steam generation. The Typhoon single-shaft industrial gas turbine is designed specifically for electrical power generation and cogeneration applications. Its application to biomass-produced fuel gas was proven in the Värnamo plant.

The second gas stream is combusted in the boiler to supplement the gas turbine exhaust heat and generate additional steam. The steam raised in the boiler is combined with that produced in the gas cooler and used to drive a 5.25 MW steam turbine. The steam leaving the steam turbine is condensed in a hybrid cooling plant and returned to the boiler.

1.1.6.2 Construction and Commissioning of the Plant

Construction work on the site in Eggborough, North Yorkshire began in the spring of 1998.

During 1998, SEC's parent company in the shipbuilding industry encountered such serious economic difficulties that it was sold, and SEC was ultimately declared bankrupt. SEC's obligations in relation to AEL gradually became impossible to meet and as a result, construction of the plant suffered significant delays during 1998 and 1999. This led to the cancellation of the O&M contract with SHP in 1999, and to AEL and SEC agreeing in 2000 to terminate the turnkey contract. Prior to agreeing to terminate, the start-up date for the plant had slipped to October 2000.

Following the departure of SEC from the project, AEL assumed direct responsibility for plant construction as well as start-up and operation (the plant's O&M activities were to be managed by a team of 25 persons directly employed by AEL) and, at relatively short notice, had to muster an engineering and site team to finalize the design and construction of what was then found to be ill-documented and poorly designed systems, the true extent of which only became fully evident once SEC's contract had been terminated. The consequential difficulties in completing the work meant that hot start-up could only be commenced in the beginning of 2001, and was then further delayed by inadequate documentation and co-ordination between sub-contractors. Figure 13 shows the ARBRE plant in June 2001.

Figure 13 The ARBRE plant in June 2001

Commissioning to mid. 2002

During the commissioning period, the plant suffered operational delays as a result of mechanical problems. However, as of mid. 2002, no long term process problems had been encountered. Most mechanical problems encountered were those associated with the movement of solids, including fuel and ash. Most of these teething problems were easily resolved, requiring only small modifications to the systems.

The fuel dryer operated without problems although its integrated operation with the rest of the plant did lead to some difficulties. As more experience with its operation was gained, the drying operation became more easily controllable.

The gasifier and tar cracker operated according to design, although operation in gasification mode did not exceed 70 % load, partly because of the limitation set by the gas cooler (see later). The switchover from combustion mode to gasification mode was rapid and trouble-free. The gasifier operated smoothly for a total period of more than 1 000 hours over ten test periods, each of varying duration. The fuels gasified included many different wood species, including that from several of the SRC plantings.

The gas quality data collected from the tar cracker, from the short periods when operating reasonably close to design conditions, indicated that expected LCV and quality could be met (Figure 14).

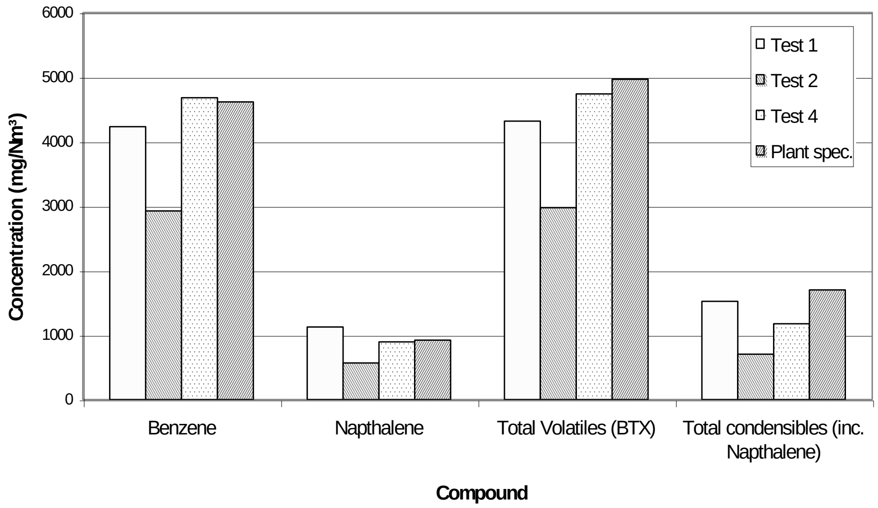

Figure 14 Tar levels in fuel gas

Mechanical problems were encountered with the fire tube heat exchanger that cooled the gas leaving the tar cracker. As the result of an error in the design calculation and from mal-distribution of the water flow beneath the tube sheet due to being designed with only one riser, the upper tube sheet of the cooler evaporator overheated such that it often limited the load at which the plant could operate. As a result of this design error, it was planned to replace this cooler in mid. 2002 with a cooler of new design. This gas cooler also suffered from clogging, in particular during start-up conditions, due to recalcination of CaO to $CaCO_3$, but was free from any tar condensation.

No operational problems were encountered with the filter. The wet scrubber was operated over long periods and, other than the need for the inclusion of a system for separation and separate removal of hydrocarbon phases formed, the wet scrubber operated according to design. After passing through the wet scrubber, the LCV gas had a heating value of ca. 5.7 MJ/Nm³.

In the beginning of 2002, the gas compressor and gas turbine were operated on LCV gas for the first time, the gas turbine operating on 70 % product gas at 80 % load for a number of hours at 3.6 MW. Emissions were as expected. During this same period, the gas compressor appeared to operate with seemingly no problems but afterwards it was discovered that two impellers suffered mechanical damage (thought to have been caused by debris left in the compressor during its installation) and needed to be replaced.

The waste heat boiler worked satisfactorily but the burner for firing the second gas stream, necessary to reach 100 % load and also to allow fresh air firing mode operation at 5 MW, had been operated only up to 50 % of its design capacity. The operational difficulties encountered were not helped by the absence of the burner supplier during its commissioning as a result of a contractual dispute. The problems with the burner were resolved by mid. 2002.

Other problems encountered with plant commissioning and operation, and the solutions applied, can be summarized as follows:

- over-integration of safety system (cautious approach): rationalization underway
- insufficient integration of digital controls: rewriting software
- expansion joint failure (wrongly positioned and specified): repositioned and improved specification
- flare clean-up design insufficient: cyclone added

Lessons learned

Project ARBRE was an ambitious project that incorporated many novel aspects. As maybe could be expected, the project encountered many obstacles during its implementation but overcame all of these to the point where the gas turbine operated on LCV gas from gasified purposely-grown SRC. During the implementation of the project, the following very important project requirements were reinforced:

- need for dedicated technical and managerial personnel
- sufficient financial resources

The main lessons learned during project implementation were:

- for innovative projects, a turnkey contract may not be the best form of contract (this depends however on the knowledge of the contractor of the process involved)
- the control system should be properly integrated

Project ARBRE has many positive operational aspects, the following being particularly worthy of note:

- fuel supply development demonstrated
- process scale-up proven to be possible
- no operational problems with CFB gasifier
- no operational problems with catalytic tar cracker
- LCV gas according to design specification
- no operational problems with bag filters
- no operational problems with gas turbine

Liquidation of ARBRE Energy Limited

ARBRE Energy Limited was placed in liquidation in summer 2002.

Ultimately, Project ARBRE failed as the result of insufficient dedicated managerial personnel. Both SEC and Kelda became involved in Project ARBRE as a result of their management's wish to expand or change their core business, SEC moving from a manufacturing basis to a project company in the new area of renewable energy and Kelda expanding their none-regulated businesses and investing in renewables projects. Changes in the management of both SEC and Kelda during the duration of Project ARBRE led to both company's changing their company strategy and ultimately withdrawing from Project ARBRE.

During 2000, Kelda failed to receive permission from the regulatory authority for requested price increases for water. This resulted in Kelda changing its strategy, and deciding it would no longer invest in environmentally-oriented commercial development. A consequence of this was that AEL was sold. From May 2002, AEL was owned by Energy Power Resources (EPR) Limited of the UK, but the final takeover was conditional on the success of operational trials at the end of 2002. The sale agreement between Kelda and EPR included an effective write-off of a significant part of the loan provided by Kelda to AEL, together with promised further write-offs once replacement financing was put in place. The agreement also included a promise from Kelda to finance the plant's commissioning activities to the end of 2002.

In July 2002, Kelda withdrew its promise of support for plant commissioning to the end of the year and despite the promising outlook for Project ARBRE as a result of the reduction in loan debts, the preferential NFFO3 contract and the imminent commercial operation of the plant, EPR indicated that they wished to place AEL into immediate liquidation, citing reasons of short term cash flow problem and long term economic viability. The EU, the Department of Trade and Industry, UK (DTI) and STEM all expressed their concern over the proposed liquidation of AEL and offered their assistance (including monetary support) to prevent such a prospect. Despite these efforts and those made by other parties, EPR placed the company in voluntary liquidation on 7 August 2002.

During the period September to November 2002, TPS had many contacts with companies showing interest in “buying” Project ARBRE, most of which expressed the wish to see the project completed as originally intended. Several of these companies also held discussions with the EU and the DTI on likely financial support.

In November 2002, bids were received from a number of companies and during December and January 2003 serious discussions were held with interested parties, following which new bids were to be received by mid. February 2003.

In April 2003, the sale of the assets of AEL to DAS Green Energy UK Ltd. (a subsidiary of BDI of USA) was completed. Talks held in 2003 and 2004, and even as late as 2006, between TPS and DAS Green Energy to complete Project ARBRE were unsuccessful. The possibility for the plant to receive funding from the EU under existing contracts is no longer available as these contracts have now expired. DAS Green Energy UK Limited itself was later also to be placed in liquidation.

4.2.7 CHEMREC

The Chemrec company (www.chemrec.se) was formed from the earlier SKF Plasma development company. The technology was bought by Kværner in 1990 and was a development company within the Kværner Pulping organization until 2000 when the majority was sold to the German company Babcock Borsig Power. In 2002 Nykomb Synergetics acquired the Babcock shares and became majority owners and in 2003 Nykomb became the sole owner of Chemrec when buying the remaining shares from Kværner.

In December 2006, Chemrec got a new majority owner when AB Volvo (the truck company) through its daughter company Volvo Technology Transfer (VTT) together with the California based venture capital fund Vantage Point Venture Partners (VPVP) took a 66 % ownership position injecting new capital into the company.

Technology

A major task of a Kraft recovery system is to recover cooking chemicals in a form suitable for subsequent use in the delignification process. A conventional recovery system has some limitations in this respect. Concepts such as split sulfidity pulping and other sulfur-modified processes are difficult and costly to implement in existing recovery systems.

The gasification-based recovery systems are more flexible, and cooking liquor compositions ranging from sulfur saturated to low sulfidity or even sulfide-free liquor may be obtained in quantities suitable for use in bleaching operations or for sulfur-modified cooking.

The core of Chemrec Kraft Recovery is the Chemrec gasifier - a refractory-lined entrained bed reactor in which concentrated black liquor is gasified under reducing conditions at around 1 000°C (Figure 15). The liquor is decomposed in the reaction zone into melt droplets consisting of sodium compounds, and a combustible gas containing H_2 and CO.

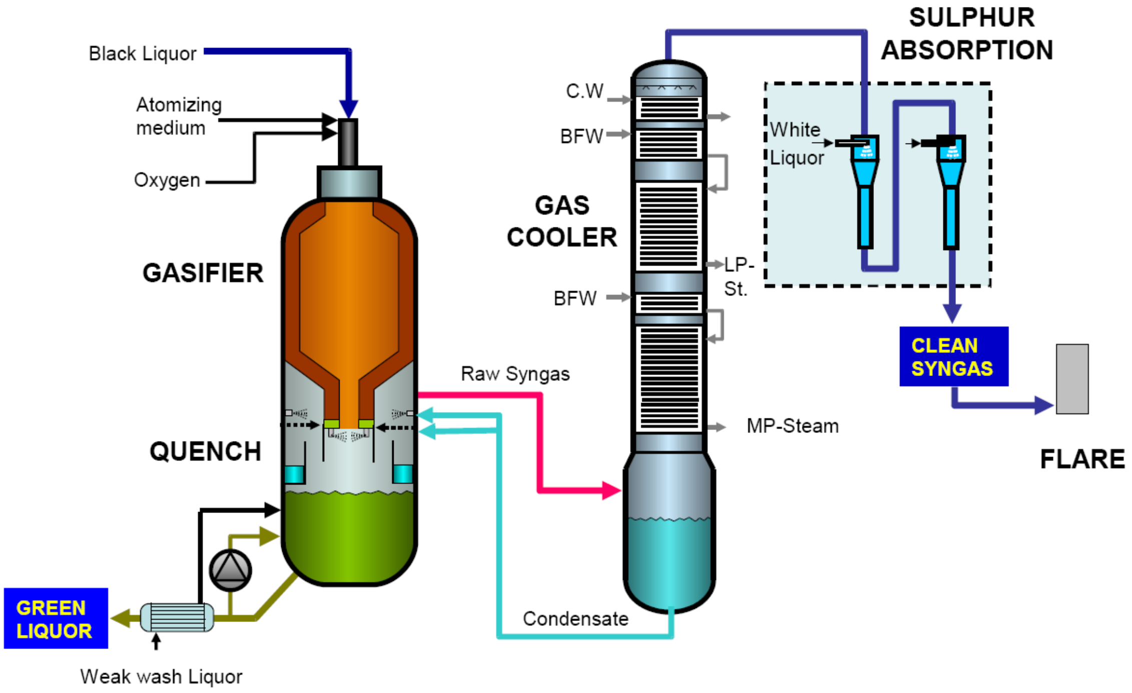

Figure 15 CHEMREC™ black liquor gasifier

The smelt droplets and the combustible gas are separated in a quench dissolver in which they are simultaneously brought into direct contact with a cooling liquid. The melt droplets dissolve in the liquid to form a green liquor solution. The gas leaving the quench dissolver is cooled producing LP and IP steam. The cooling is done in counter current mode which means that the gas is efficiently washed of particulate matters. The gas is then free of melt droplets and can be scrubbed for H_2S removal and then used as a clean fuel or syngas.

The three major applications for the CHEMREC Recovery technology are:

1. CHEMREC™ Booster
- Relieve overloaded recovery boilers
- Capacity expansion projects

2. CHEMREC™ - BLGCC
- Replace old recovery systems (Tomlinson boiler)
- Recovery technology for green-field mills with improved power yield

3. CHEMREC™ BLGMF/H2
- Replace old recovery systems (Tomlinson boiler)
- Recovery technology for green-field mills
- Production of synthesis gas for generation of Black Liquor Gasification Motor Fuels

Emerging recovery technologies based on gasification and energy recovery in advanced gas turbine cycles promise substantial improvements in energy and environmental performance. Besides a higher power to heat ratio, the CHEMREC IGCC system (Table 5 and Figure 16) has a higher thermal efficiency relative to a recovery boiler / steam cycle. This has a beneficial impact not only on emissions but also on the supply of steam and power to the mill.

Table 5 CHEMREC™ vs. Recovery boiler, energy flows for co-generation

	Modern recovery boiler	CHEMREC™ IGCC
Electricity	14-16 %	22 %
Steam	54 %	~50 %
Losses	~30 %	25-28 %

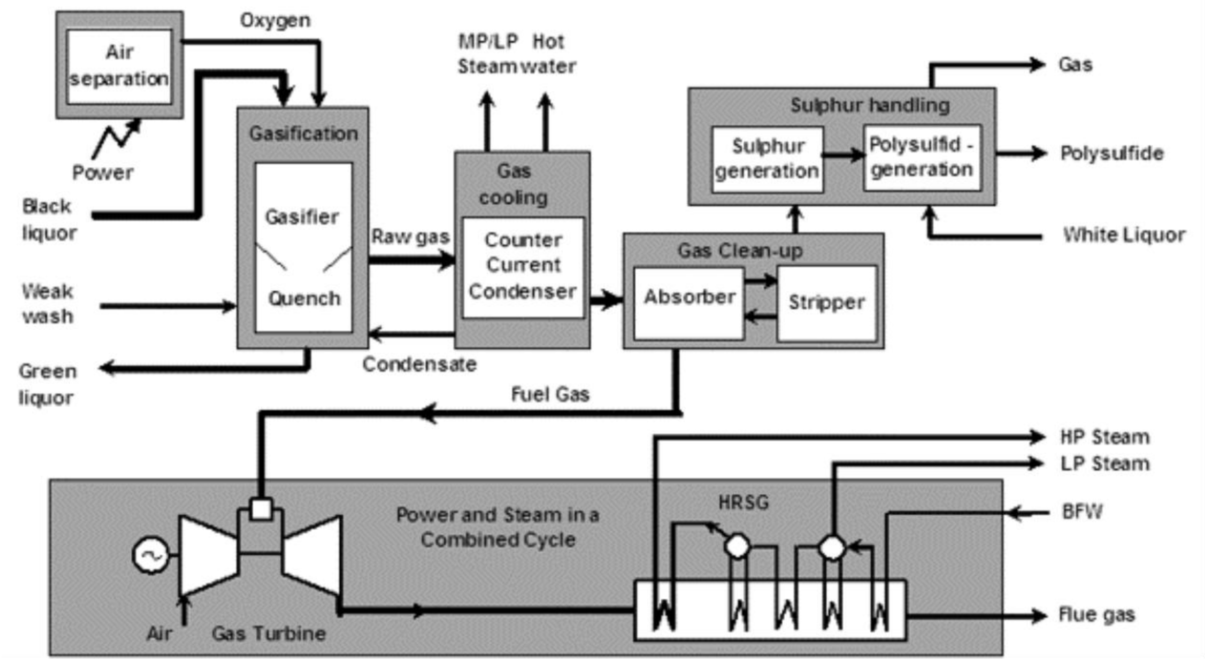

Figure 16 CHEMREC™ BLGCC Technology

The increased thermal efficiency and higher power to heat ratio in a CHEMREC™ IGCC system increases the potential for power generation to the range 1.8-2.0 MWh / ADMT (Air dry metric tonne of pulp) from substantially lower figures in today's most advanced recovery boiler steam cycle systems. The current CHEMREC™ IGCC concept is based on oxygen as oxidant.

Oxygen-blown gasification is an advantage also in light of the increasing use of oxygen chemicals in the modern mill. For the BLGMF concept, this is a prerequisite.

When considering synthetic motor fuels, the combination of synthesis gas generation with the heat sinks available in the pulp mill means that not only can a good conversion efficiency be achieved from black liquor, but more importantly, the extra biomass fuel required to compensate for the loss of fuel value in the motor fuel product gives a > 65 % efficiency of conversion. The cost of production of motor fuels is low due to the high biomass to fuel conversion efficiency combined with a relatively low investment. A key reason for the low investment is that the BLGMF technology (as well as BLGCC) is introduced in the mill as a substitute for the recovery boiler at a time when it needs to be replaced.

Chemrec commercialization

The Chemrec development milestones are highlighted in Figure 17.

- **Atmospheric pilot plant, 3 tDS/24 h, SKF, Hofors, 1987**
- **Booster demonstration plant, 75 tDS/24 h, AssiDomän, Frövi, 1991**
- **Pressurized air-blown pilot plant, 6 tDS/24 h, Stora Enso, Skoghall, 1994**
- **Commercial Booster plant, 300 tDS/24 h, Weyerhaeuser, New Bern, 1996**
- **Pressurized oxygen-blown rebuilt pilot, 10 tDS/24 h, Stora Enso, Skoghall, 1997**
- **Start-up of the rebuilt, second generation Booster plant, Weyerhaeuser, New Bern, June 2003.**
- **Pressurized oxygen-blown Development Plant, 20 tDS/24 h, Kappa Kraftliner, Piteå, start-up 2005.**

Figure 17 Chemrec development milestones

A CHEMREC™ Booster atmospheric-pressure demonstration plant has been operating successfully for some time at AssiDomän's Frövifors mill in Sweden. The capacity corresponds to 75 tonne per day of black liquor solids. The CHEMREC™ Booster system is targeted to relieve overloaded recovery boilers, and unlike retrofitting a recovery boiler, this system can be installed without any interruption in pulping operations. A commercial facility of 300 tonne dry substance per day capacity has been in operation at the Weyerhauser New Bern pulp mill in USA since 1996 (Figure 18). In the initial stage of operation, refractory lining deterioration led to too short intervals between ceramic replacements. The stainless steel reactor shell was cracked due to SCC (stress corrosion cracking) and taken out of service in 2000. After a long development and engineering effort, a new carbon steel reactor was installed and the plant was restarted in June 2003. The last ceramic lining lasted 24 months before it was replaced in October 2006. An even longer lifetime is expected for the current lining.

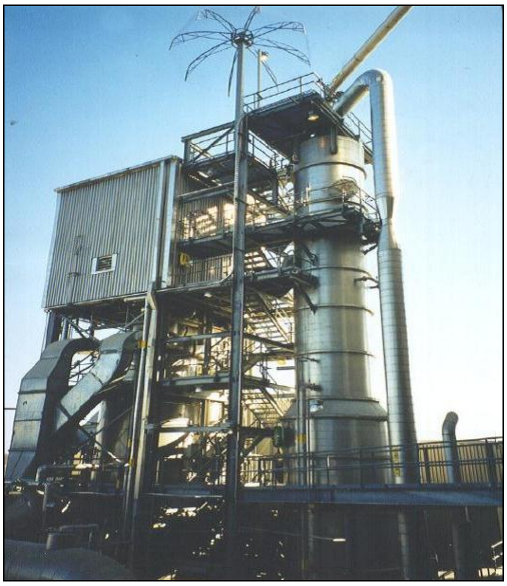

Figure 18 Commercial Booster plant at New Bern

Gasification of black liquor under pressurized conditions, a pre-requisite for IGCC operation based on the CHEMREC™ concept, has been performed and tested in a small pilot plant in a mill in Karlstad, Sweden. A commercial-sized demonstration was planned for 1998-99 but was delayed A grant from the Swedish state (237 million SEK, €26 million) was allocated to the project.

The DP1 pressurized pilot plant and commercial developments from 2010 and onwards is described in the main Country Report 2012.

4.2.8 Scanarc / Pyroarc (plasma) process - www.scanarc.se

The Plasma Gasification technique evolved from the metallurgical process developments by SKF Steel in Sweden. In attempts to produce reducing gas for iron manufacture, a plasma was introduced in the bottom of the shaft producing H_2 and CO from coal and air. The effectiveness of the plasma in this application was high, leading to a number of proposed processes.

Two of these processes were installed at full-scale: the PlasmaZinc and the PlasmaChrome for handling zinc dust and chrome materials. Several processes for coal gasification using the Plasma Gasification technique were designed during the early 1980's, however none were realized.

Following the fall in energy prices, the interest during the 1980's focused on Plasma Gasification as a tool in waste handling, in particular, for special types of waste such as hazardous wastes, medical wastes, etc.

The ScanArc (former "SKF Plasma") process is a fixed bed, high temperature process producing a molten slag. The gasification is carried out in an updraft shaft.

Differences with other processes are in the means to achieve the high temperature and in the cleaning of the raw gas. In the ScanArc process, the gas cleaning is achieved in a plasma where the gas is heated to very high temperatures, causing a decomposition of tar, chlorinated hydrocarbons and ammonia.

<u>Process description</u>

The PyroArc process utilizes the unique properties of plasma technology to achieve complete decomposition of organic substances and to transform them into a clean fuel gas. The process is suitable for nearly all types of waste including hazardous waste. The PyroArc is well suited for recovery of metals and energy from hazardous waste containing organic compounds (e.g. oil, dioxins, PCB, halogens) and / or heavy metals. The pilot plant in Hofors has tested a wide range of these types of waste with good results. Several patent applications for this process have been submitted, and are pending. Solid waste is fed into the shaft gasifier through a lock hopper system. The ScanArc process (Figure 19) uses a shaft reactor and is fed in the middle with a mixture of air and oxygen. Non-combustible material is discharged from the shaft as liquid slag or metal about 1 450°C, while the gas - including halogenated aromatic hydrocarbons - exits from the top of the gasifier at 400-600°C. Oxygen is needed when the effective heat content of the wastes is too low to achieve a temperature of 1 200°C or more. For fuels to the reactor with heat contents above 10-15 MJ/kg, this constitutes no problem. These heat contents are, however, not always met with MSW unless other wastes are added.

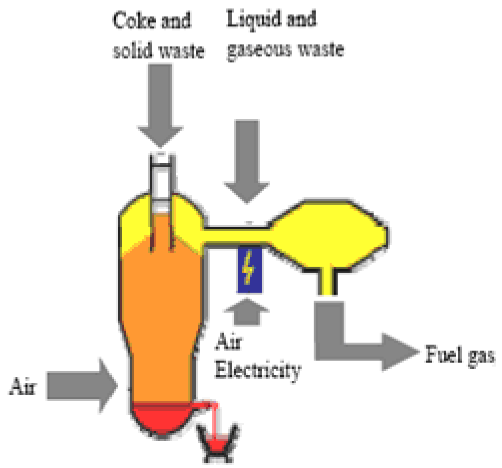

Figure 19 SKF Plasma / ScanArc

The raw gas is fed to a second reactor which is more or less an empty shaft with a plasma generator on top. The electric plasma generates a theoretical temperature of more than 15 000°C through which the gas is passed (thus, lowering the temperature) into the shaft. The fuel to the plasma is composed of electricity and air for combustion (oxidation). After the second reactor, chlorine is present as Cl_2 or HCl, nitrogen as N_2, etc., i.e. all organic compounds and several others are decomposed.

After the plasma reactor, the gas is cooled and washed. The fly ash is collected and may be sent for recovery of some metals since they are separated in a reduced state. Besides the wash water, a “clean” gas and hot water is obtained. Available data do not provide information as to what extent flue gas treatment is required after combustion.

Only few data are revealed from the process. The power consumption for the plasma is reported as 200-400 kWh/tonne of feed - depending on the heating value of the feed. These figures imply an energy efficiency of roughly 65-80 %, calculated on the gas and the hot water.

Status

The ScanArc gasification is tested on MSW in a pilot unit. The gasification is designed for capacities of 50-100 000 tonnes per year and in this range the investments are said to be US$ 700-1 000/tonne of feed (1997 figure).

Offers based on MSW have been made, but no unit has been installed. At present, the ScanArc gasification focuses on hazardous wastes where higher requirements on the process can more easily afford the technique. In 2007, ScanArc Plasma Technologies and ERAS Metal was bought by ScanArc ASA. In 2011, 80.1 % of the shares in ScanArc Plasma Technologies were bought by Valeas Recycling Solutions AB, a company owned by present and previous management of ScanArc Plasma Technologies AB. There has been little apparent activity in Sweden during the last few years.

5. ACKNOWLEDGEMENT

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