Biomass IGCC at Värnamo, Sweden – Past and Future

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0. Abstract

Sydkraft AB has built the world's first complete IGCC Power Plant which utilizes wood as fuel. The plant is located at Värnamo, Sweden, and the technology used in the power plant is based on gasification in a pressurized circulating fluidized bed gasifier. The gasification technology is developed in co-operation between Sydkraft AB and Foster Wheeler Energy International Inc.

The plant at Värnamo feeds about 6 MW electricity to the grid, as well as 9 MW heat to the district heating system in the city of Värnamo, from a total fuel input equivalent to 18 MW. The plant is an important step forward in developing highly efficient and environmentally acceptable technologies based on biomass fuels. The accumulated operating experience per 1999 amounts to about 8 500 hours of gasification runs and about 3 600 hours of operation as a fully integrated plant. The test runs have been very successful and the plant has been operated on different wood fuels as well as straw and RDF.

The Demonstration program was concluded in 2000 and the plant has been mothballed since then since it is not economical to operate given the commercial conditions prevailing in Sweden. However, significant efforts have been made to make use of the relatively large research facility and for this purpose a new company Växjö Värnamo Biomass Gasification Centre (WBGC) has been established in December 2003. This safeguards access to and availability of the plant, including the use of qualified staff for projects interested to use the Värnamo plant.

The major projects planned for WBGC that will use the Värnamo plant are:

- Development of IGCC application for refuse derived fuels
- Production of clean hydrogen-rich synthesis gas
- Rebuild of pilot plant to incorporate production of alternative motor fuels

Results from the previous operation and future plans for the Värnamo plant is discussed in this paper.

1. Introduction

The Värnamo IGCC Demonstration Plant (6 MWe/9 MWth) in Sweden is the first of its kind in the world. It 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 plant was aimed at demonstrating the complete integration of a gasification plant and a combined cycle plant, fuelled by biomass. The basic idea is 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 R,D&D activities.

The Demonstration Program was concluded in 2000, some results of which are reported below. Final reports concerning Värnamo Demonstration Plant, Construction and Commissioning 1991-1996 and Värnamo Demonstration Plant, The Demonstration Program 1996-2000 are available from Sydkraft AB, SE-205 09 Malmö, Sweden.

Figure1: Aerial view of the Värnamo Demonstration Plant

The plant in Värnamo is presently owned by Sydkraft but negotiations are ongoing to sell the plant to a newly established company for further use as a research and demonstration facility. In order to guarantee the availability of the plant by public funding, a non-profit project-based company has been established at Värnamo. This arrangement safeguards access to and availability of the plant, including the use of qualified staff for projects interested to use the Värnamo plant.

The major projects planned for VVBGC that will use the Värnamo plant are:

- development of IGCC application for refuse-derived fuel (RDF) and other waste fuels, including waste tires, i.e. the VÄRNAMO - WASTE project.
- production of clean hydrogen-rich synthesis gas, i.e. the CHRISGAS project.
- rebuild of pilot plant to incorporate production of alternative motor fuels.

2. The IGCC process as it stands today

A simplified process diagram and the components of the gasification plant are shown in Figures 2 and 3.

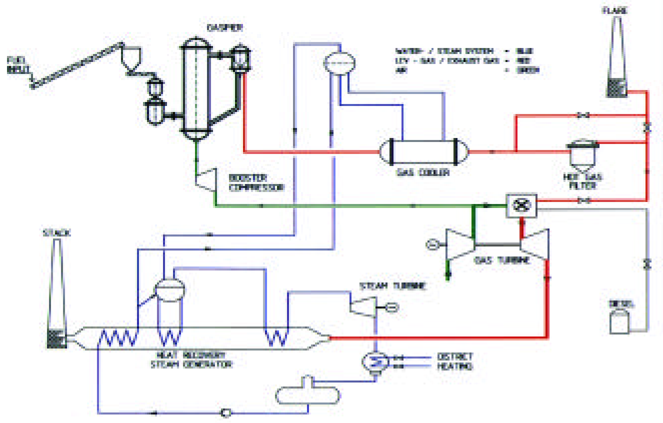

Figure 2: Process diagram

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 circulating fluidized bed and consists of the gasifier itself, cyclone and cyclone return leg. These three parts are fully refractory lined.

The gasifier is air-blown. About 10% of the air is extracted from the gas turbine compressor, 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. The combustion maintains the required temperature in the gasifier.

After 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 a temperature of 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.

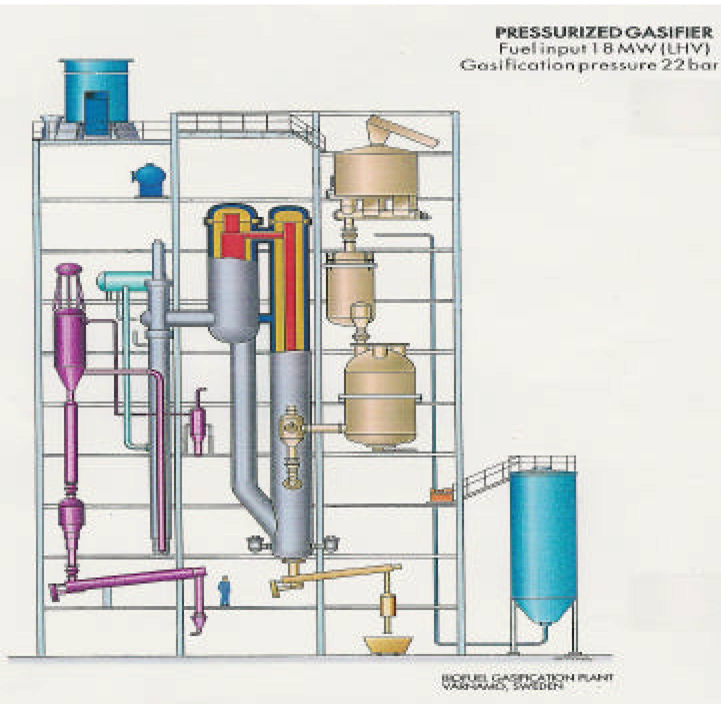

Figure 3: Cross section of the Värnamo gasification plant

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 have been redesigned to suit the low calorific value gas (5 MJ/nm^3).

The hot flue gas from the gas turbine is ducted 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, which is used during start-up and to protect the gas turbine when testing less well known conditions.

Table 1: *Technical data of the Värnamo Plant*

Power/heat generation	6 MWe / 9 MWth
Fuel input	18 MW fuel (85% ds)
Fuel	Wood chips. (Several other fuels have been tested with good results.)
Net electrical efficiency (LCV)	32%
Total net efficiency (LCV)	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
Plant owner	Sydkraft AB

Suppliers:	
Engineering	SYCON / Foster Wheeler
Gasifier	Foster Wheeler
Gas cooler	Foster Wheeler
Ceramic hot gas filter	Schumacher GmbH
Metallic hot gas filter	Mott Corporation
Gas turbine	European Gas Turbines
Booster compressor	Ingersoll-Rand
Heat recovery steam generator	Foster Wheeler
Steam turbine	Turbinenfabrik Nadrowski GmbH
Plant control system	Honeywell

3. Demonstration/development program

An extensive demonstration/development program was carried out during 1996-2000. The work was partly performed in collaboration between Sydkraft, Foster Wheeler, Electricité de France and Elkraft. It was also partly financed by Elforsk AB, Sweden, The Swedish National Energy Administration and the European Commission.

The overall aim of the program was to verify the status and future potential of the biomass IGCC concept, utilizing the Bioflow (joint venture between Foster Wheeler and Sydkraft) technology from a technical and economical 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 is verification of the quality of the gas produced in the gasifier, as well as the operation of the gas turbine.

In parallel to the test runs, extensive work to estimate investment, operational and maintenance cost for future plants, based on experiences from the Värnamo plant, was performed.

4 Experience gained during test operation

4.1 General

Commissioning of the plant started in late 1992 and the commissioning of the combined cycle was completed on liquid fuel during March 1993. The first gasification test on wood chips at low pressure was performed in June 1993, and combustible gas was produced and burned in the flare.

It should be remembered that at the time of commissioning of the gasifier, no experience existed from any biomass gasifiers at the higher pressure level. During tests with different bed materials, temperatures and pressure levels, deposits sometimes occurred, verifying the importance of carefully controlling the process as well as ensuring suitable design of components. During the Demonstration Program, magnesite (MgO) had been used as bed material in the gasifier, and this proved to be very successful. As magnesite is more expensive than dolomite, tests were carried out to check the feasibility of re-circulating bottom ash, and thus reusing the magnesite drained from the system, these tests proved to be very successful. However, it is still believed that it will be useful to continue testing different bed materials or mixtures of bed materials to further optimize the gasification process and achieve the best result i.e. minimum of deposits, cost and best possible gas quality. On the other hand, significant deposits can also be handled with a suitable design of gasifier and downstream components.

Apart from this, already during the early design stage, two areas of particular concern were gas clean-up and gas quality.

The idea behind the hot gas filtration 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. As the amount of benzene and tars is not insignificant from a gas heating value point of view, this is very important to achieve.

Figure 4 shows a typical operating curve for the hot gas filters, clearly showing that no continuous increase in pressure drop is taking place.

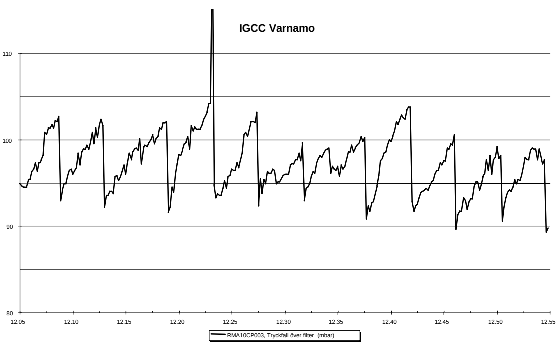

Figure 4: Pressure drop in a hot gas filter cleaned by nitrogen pulsing

4.2 Gas quality

During the commissioning as well as 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 2.

Table 2

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

Percentage in Table 2 is by volume and gas heating values in the range of 5.0 - 6.3 MJ/m^{3}n have been recorded.

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 3. Bark tends to produce less benzene and tars than ordinary wood chips.

Table 3

Fuel	Benzene mg/m^{3}n	Light tars, mg/m^{3}n
Bark 60% and forest res. 40%	5 000 - 6 300	1 500 - 2 200
Pine chips	7 000 - 9 000	2 500 - 3 700

During almost all tests, it was general practice to measure not only main gas constituents, but also benzene and light tars. An interesting correlation between the amount of light tars and benzene in the product gas has been noticed, which can be seen in Figure 5.

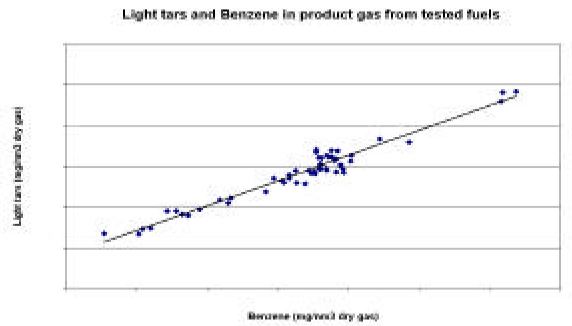

Figure 5: Amount of light tars vs benzene in product gas

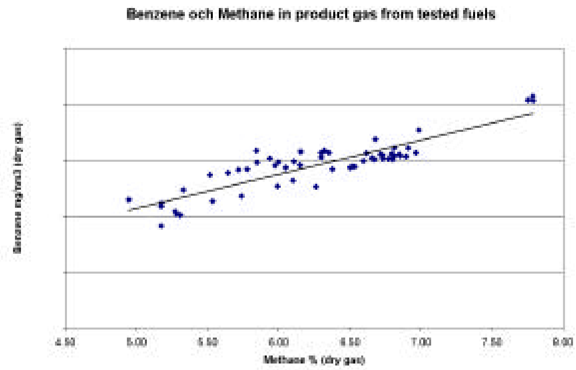

Figure 6: Measured amount of benzene vs methane in the product gas

Due to the relatively low combustion temperatures in the gas turbine combustors when burning product gas, thermal NO_x is very low. Total NO_x emissions can however be higher compared to operation on liquid fuel with steam injection due to the conversion of fuel bound nitrogen into NO_x. Figure 7 clearly shows the influence of the amount of fuel bound nitrogen on total NO_x emission.

The recorded levels of alkalines have been below 0.1 ppm wt.

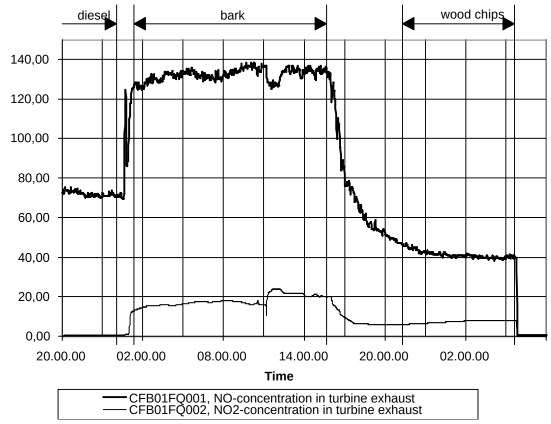

Figure 7: Gas turbine exhaust emissions

4.3 Hot gas filter performance

Originally, a ceramic hot gas filter was installed. This filter consisted of ceramic filter candles arranged in six groups with separate back-pulsing.

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 problem of detecting a relatively small failure in a hot gas filter was then evidenced in practice even though no serious damage was caused.

Although the broken candles as well as other candles from the filter were analyzed, no reason for the breakdown was traced by the supplier. The complete set of candles was changed to a new design of ceramic candles and this was installed in the plant. After less than 350 operating hours one of the new type of candles broke. The breakdown was determined by the supplier to be caused by mechanical fatigue since micro cracking was found in all tested elements, and chemical attack was excluded.

To find possible reasons for the mechanical fatigue, measurements inside the pipe (noise) as well as in pipework and steel structure were made. Vibrations were verified to be very low. Finally, to avoid any risk of fatigue, grids supporting the candles were installed. However, since the installation of this grid a tendency of bridging has been observed, which was not experienced earlier.

To protect the gas turbine in case of a hot gas filter breakdown, a metallic police filter was installed downstream of the main filter. Shortly after this installation was completed, another failure of the main filter occurred. From Figure 8 it can be seen that the pressure drop over the police filter increases rapidly, whereas it was hard to spot the broken candle from measurements of the pressure drop across the main filter.

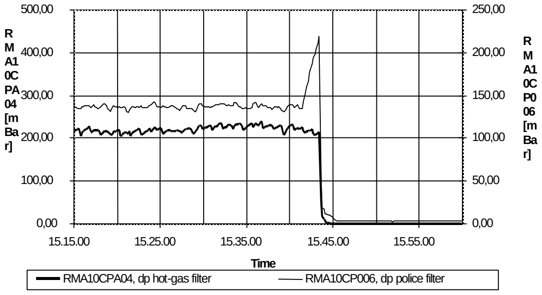

Figure 8: Hot gas filter failure

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 are installed in the original filter vessel but with a new tube sheet and back-pulsing arrangement.

The metal filter has, like the ceramics, shown 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 these elements although they had been exposed to gas and ash not only from wood chips but also from RDF and straw.

4.4 Gas turbine experience

The gas turbine installed in the plant is almost a standard Typhoon from ABB Alstom Gas Turbines in Lincoln, England (now operating as Demag Delaval Industrial Turbomachinery Ltd, a wholly owned subsidiary of Siemens). Modified components are the combustors, the burners and the addition of an air bleed from the compressor. Furthermore, a special design gas control module had been developed to control the product gas, steam and nitrogen to the unit.

In September 1995, commissioning of the modified gas turbine on liquid fuel was completed, and the first test runs on product gas were performed in October. In order to minimize the risks, the first test runs were very short and the product gas was introduced gradually with a corresponding reduction in liquid fuel, which eventually resulted in operation solely on product gas.

Already prior to being supplied to Värnamo, the special combustors and burners were tested in a rig in England utilizing synthetic gas. Combustion has always been 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) proved to be 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 was it necessary to maintain a pilot flame of liquid fuel and thus operation during all 3 600 hours has been on 100% gas and no liquid. This is valid within the full operating range, i.e. from 40% to full load.

Internal inspection of the turbine and combustors was carried out after every test run and it can be said that the hot gas clean-up is operating satisfactorily and no damage to the mores sensitive parts of the turbine, etc. has been observed.

Complete combustion of the hydrocarbons has always been achieved with emissions between 1 and 4 ppm only, whereas a slightly high figure of CO has been observed with figures up to and sometimes even above 200 ppm on part load. Work is on-going to improve this.

As has been mentioned before (Figure 7) levels of NOx around 150 ppm were recorded when operating on gas produced from biomass with high nitrogen content (like bark) while the lower nitrogen content of hardwood considerably reduces the NOx down to as little as 50 ppm. Recent tests on 100% straw, which is a nitrogen-rich fuel (about 1% of dry fuel) have produced a NOx emission of slightly above 250 ppm.

The development of new combustors will reduce the formation of NO_x and further development of selective catalytic oxidation (SCO) of NH_3 and HCN will most likely further reduce the emissions. Conventional SCR technology, the cost of which has recently been reduced, can of course also be used.

In the early days of the project, the capability of a small gas turbine to burn a low calorific value gas was of concern. In 1995, it was shown in Värnamo that the gas normally produced by the gasifier (i.e. a heating value of 4.5 MJ/kg) could be burned without the use of a pilot flame. As flame stability during all tests was not a problem, the gas quality was deliberately and gradually reduced to find out when flame-out would occur. In Figure 9, this is shown. Since the engine was running at about 50% load and steam was used to dilute the gas it is likely that operation could have been maintained also at a lower value than the one achieved (< 3.8 MJ/kg) during less extreme conditions.

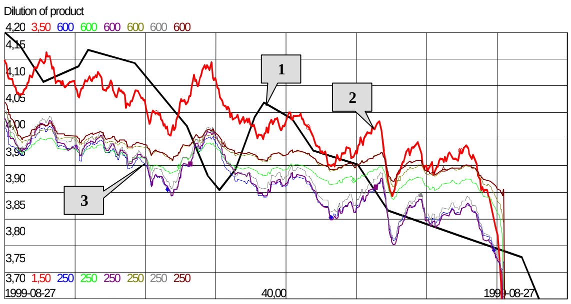

Figure 9: Test of gas turbine flame-out

(1)	Gas LCV (MJ/kg)
(2)	Gas Turbine output (MW)
(3)	Gas Turbine exit temperature (ºC)

4.5 Fuel flexibility

The fuel feeding system with the lock-hopper, pressurized fuel silo and screw feeders is primarily designed for wood chips and fuels with similar density/heating value per m^3. During commissioning and the first years of testing, forest residue and wood chips were the fuels generally used. A number of different fuels have however been tested in the plant during the last couple of years. Fuels with very low density are of interest from the gasification point of view. These low density fuels have to be pelletized due to the type of fuel feeding system installed. Accordingly, straw, willow, bark and saw-dust pellets have been tested. For testing purposes, it is also beneficial to be able to mix different types of fuels to a pre-determined ratio and this is of course considerably easier with the fuels in pelletized form.

The following fuels have been tested:

- Wood chips.
- Forest residue (bark, branches, etc.).
- Saw dust and bark pellets.
- Willow (salix).
- Straw.
- RDF.

All these fuels have proved to be easy to gasify without causing deposits or sinter in the systems. The gas produced when operating on wood chips made from hard wood contains more benzene and tars than forest residue containing bark, as shown in Table 3. Bark has proved to be an excellent fuel and even feed rates up to 100% bark is easily gasified and the gas is very good for filtration and gas turbine operation.

The rather high levels of alkalines in willow (salix) have not caused any problems in any part of the system and the amount of sintered/agglomerated material in the bottom ash was very small. Tests have been performed with willow in pelletised form, from small amounts up to 100%. The only clear and negative effect observed was a reduction in heating value of the gas. However, this change was not significant and gas turbine operation was not affected.

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, but more recently tests with 100% straw were performed. 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 excellent for gas turbine operation.

The tested RDF was in a pelletised form produced from waste paper, plastics, cardboard, alumina, etc. The size of these pellets was larger than that used for most other fuels (18 mm vs 8 mm). Tests with up to 50% RDF were carried out, the make-up fuel being sawdust and bark. Encouraging results were achieved, including gas turbine operation on the gas produced.

4.6 Plant control experience

During normal operation, the flare valve is closed and the pressure in the gasifier is controlled through a by-pass valve at the booster compressor. Concerning both pressure and temperature control, the gasifier is a “slow system”. The output control of the gas turbine is different as it responds more or less instantaneously. Operation in the fully integrated mode made the pressure, temperature and gas quality in the system vary a little when the gas turbine suddenly compensated for a small change in either parameter.

This feature of the Bio-IGCC was apparent already during the design stage of the project, and the gas turbine supplier was asked to operate the unit with the control valve “fully open”. This way of operation will have several benefits (lower pressure in the gasifier, reduced requirement of auxiliary electric power, etc.). It should also have a positive effect on the conditions in the gasifier. A test simulating this was performed and the results are shown in Figure 10. Gradually, all parameters in the gasifier stabilize completely and since the process runs smoother the variation in output from the gas turbine is very small.

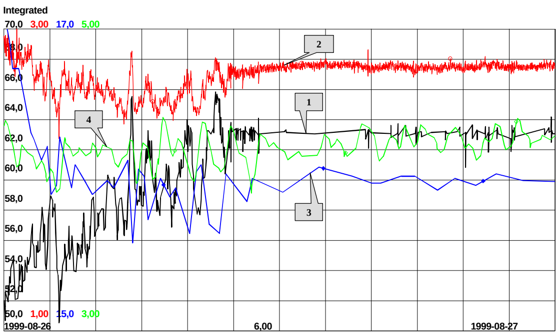

Figure 10: Plant output control (First GT control → Gasifier control)

(1) Gas turbine valve position (%)
(2) Gas flow (kg/s)
(3) Gasifier pressure (bar)
(4) Gas LCV (MJ/kg)

5. Conclusions from the demonstration program

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, has been very successful and has proven that pressurized biomass IGCC technology works. The best proof of this is the achieved number of operating hours. The complete plant has been in operation with the gas turbine operating solely on product gas produced by the gasifier in excess of 3 600 hours. Huge experience has been gained from gasifier operation for more than 8 500 hours. Results achieved can thus be summarized as:

- 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 below detection level also for chlorine-rich fuels.
- The biomass gasification technology is very suitable for retrofit to existing NGCC.

6. Formation of Växjö Värnamo Biomass Gasification Centre

In order to guarantee the availability of the Värnamo plant by public funding, a non-profit project-based company under the control of Växjö University, has been established at Värnamo by Värnamo Energi AB and Växjö Energi AB. This arrangement safeguards access to and availability of the plant, including the use of qualified staff for projects interested to use the Värnamo plant. Växjö Värnamo Biomass Gasification Centre (WBGC) was incorporated in December 2003. It is planned that in the future WBGC will become an affiliate of Växjö University, and that it may also include other higher education organisations as owners, possibly also other entities.

The major projects planned for WBGC that will use the Värnamo plant are:

- development of IGCC application for refuse-derived fuel (RDF) and other waste fuels, including waste tires, i.e. the VÄRNAMO - WASTE project.
- production of clean hydrogen-rich synthesis gas, i.e. the CHRISGAS project.
- rebuild of pilot plant to incorporate production of alternative motor fuels.

7. The Värnamo – Waste Project

Helector S.A., Greece, Sydkraft, Sweden and CRES, Greece have signed a contract with the European Commission, within the EC Framework 5 program, aiming to demonstrate IGCC operation on Refuse Derived Fuel (RDF) and to some extent operation on used Tires Derived Fuel (TDF). The Värnamo plant will be refurbished and re-started. Some modification of the plant is also necessary in order to limit the emissions of e.g. sulphur. As a measure to handle this problem, additional testing in a pilot plant will be conducted to test an innovative H_2S removal device and the performance of this system will be evaluated and reported. Also a new fuel feeding and pressurization is considered to be installed to handle fluffy RDF, which is expected to decrease the nitrogen consumption compared to previous operation of the Värnamo plant.

8. Synthesis gas production in the Värnamo plant

An analysis by the Swedish government identified the development of synthesis gas generation from biomass as a key technology for large-scale, cost-efficient production of liquid biofuels. In 2001, several industrial companies put together a proposal to use the plant to produce 10 000 tonnes/year of bio-DME. However, it was concluded by the industrial companies involved that the technical risks involved (in economic terms) were too large to be borne by themselves alone. Despite this, two important conclusions emerged from these deliberations, firstly, the facility could only succeed if it was transferred to a development centre under public control, and secondly, the facility could in addition to IGCC development also be used, after modifications and extension of the equipment, for gasification to synthesis gas and automotive fuels.

Since 2000, efforts to create new partnerships to maintain and utilise this unique facility have been made and two such efforts have met with success.

During the period 2004-2006, the plant will be utilised for the gasification of waste fuels to develop an advanced WtE (waste-to-energy) concept in the EC Framework 5 “VÄRNAMO - WASTE” project, as described above. In parallel, and extending through to 2009, the CHRISGAS project will be operated, using the plant for oxygen-blown gasification to generate synthesis gas from biomass. Use of the site for gas turbine developments and addition of downstream units to utilise the synthesis gas produced for production of liquid fuels, fuel cells, etc. are also planned to commence in 2006-2007.

The CHRISGAS project
The primary objective of the CHRISGAS project is to demonstrate in the Värnamo plant the manufacture of a hydrogen-rich gas from a renewable feedstock, i.e. biomass.

The project consists of research and development activities, research-related networking activities, training activities and dissemination activities as well as socio-economic research of the non-technical obstacles for penetration into markets of the technologies concerned.

The demonstration part of the project consists of a number of tasks for which the objectives are:

- Conversion of several solid biofuels 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 will be conducted, the objectives of which include:

- 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 biofuels, 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 2004 and 2005, the planning of the modification of the plant for the CHRISGAS project will be made, partially based on support from some parts of the R&D program. After the VÄRNAMO - WASTE test program is complete, plant alteration will commence and once the plant is ready for operation again, test work in the CHRISGAS project will begin.

Advancement of state-of-the-art
The innovative aspect of the CHRISGAS project is to develop the basis of technology of the unproven processing steps in the initial generation of gas generated from biomass and its cleaning, and to examine the entire green vehicle fuel production chain. This approach comprises of several innovative elements in the various work packages of this project, mainly focusing on the gasification-gas cleaning steps which are less developed than upstream or downstream process steps but which are the key to cost-efficient production of a hydrogen-rich synthesis gas for upgrading to vehicle fuels.

The results of the CHRISGAS project will not only be beneficial to the production of synthesis gas from biomass, but also for the production of renewable electricity by IGCC systems, in which pressurized gasification often is used to generate a low calorific value gas for use in gas turbines, and which utilizes similar equipment and processes.

Detailed outline of the work program of the CHRISGAS project
<u>Demonstration activities</u>
The “Demonstration” parts of the project aim to prove, in the Värnamo plant, the viability of new technologies for the production of a hydrogen-rich gas. This facility will include the full process from fuel feeding to a hydrogen-rich gas suitable for further upgrading, and, with time, downstream steps may be added in side-stream or full scale, these sections and items being developed and tested as part of the CHRISGAS project.

To fulfill these goals, and also to expand to actual production of liquid biofuels at a later stage, the IGCC plant at Värnamo will require significant rebuilding. The initial modifications, to allow operation on oxygen, will be based partially on support from some parts of the supporting R&D program and are due to be completed in 2008, after which pilot plant test work shall commence. This test work shall include initial tests made on wood fuel with the purpose of gaining experience with operation of the new plant components. The output of the plant, when operative in this mode, will be a hydrogen-rich gas suitable for further upgrading to synthesis gas or commercial quality hydrogen which can then be processed into e.g. a new synthetic vehicle fuel.

It is planned that at the end of 2008 and during these tests, further expansion of the plant to include e.g. acid gas removal unit, make-up gas (MUG) compressor and a synthesis section will take place, this second step being an extension of the CHRISGAS project. The raw, hydrogen-rich synthesis gas fed to such downstream units has to be high quality and at elevated pressure. The higher the operating pressure, the better for the synthetic fuel production downstream, and therefore a pressure downstream, after final compression, of between 60 and 100 bar will be required. Following these modifications, other fuels, having been targeted as the most likely feedstocks in various areas in Europe can be tested. During this same period, results from internal and external R&D work will be included as R&D elements, at the appropriate time and appropriate scale, e.g. as small side-stream tests of catalysts and sorbents, filter element design.

The proposed modifications to the Värnamo plant can be seen in Figure 11. The most important changes proposed are:

- 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 catalytic high temperature reformer is installed.

Note that the gas turbine is still in place as WBGC 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. Installation of this feeder would allow use of agrofuels in the plant without costly pre-treatment in the form of pelletisation, thereby expanding the suitable fuel spectrum.

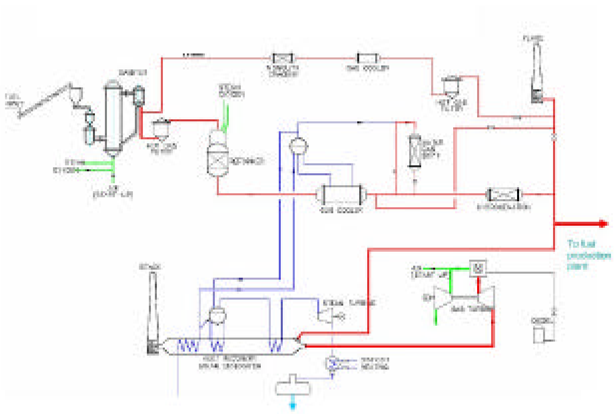

Figure 11: Värnamo biomass-fuelled IGCC process scheme, after proposed rebuilding (Phase 1)

<u>Fuel feeding</u>

In order to secure a cost-effective production of product gas through pressurized gasification it is essential to develop and integrate a feeding system with low operational costs. One of the main conclusions from the Värnamo demonstration project from 1996-2000 was that the high inert gas consumption of the existing lock hopper system represented a relatively high proportion of the operating costs of the plant. One of the original intentions was to test a feed system based on a piston feeder, but unfortunately there were no opportunities for testing such a system. This may now be done as part of the CHRISGAS project. The plug feeding consists of a plug section where the biomass is compressed to form a plug, a feeding mechanism to press the biomass into the plug section and a mechanism to control the density in the plug section. The advantage of plug feeding is 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. For low density materials such as agro fuels, plug feeders are even more attractive than for wood fuels.

<u>Gas cleaning</u>

The conversion of solid biomass into a medium calorific gas calls for new innovative solutions mainly in the gas cleaning process but also in the catalytic reforming of the product gas to synthesis gas. Components that are to be developed include a high temperature gas filter. An improved back pulse system for the hot gas filter and an improved filter element fixation system are some of the main issues to be considered. In the gas cleaning process, operational tools for quality control of product gas and an appropriate method for sulfur capture are also to be developed. Reforming of a product gas containing tar, methane and light hydrocarbons, to synthesis gas that can be used as raw material in biofuel production (CO and H_2) will be tried, preferably by using a catalyst. Innovation-related activities in the development of such a catalyst will be to enlighten and overcome the problems with decay and deactivation of the catalyst caused by particulates and poisoning.

R&D activities

The R&D technical and experimental tasks in this project performed at sub-pilot scale will run mostly in parallel to the R&D and demonstration efforts in the Värnamo plant. Some aspects addressed in these tasks will form part of the design basis for rebuilding the plant, however, the majority of the tasks address supporting research or improved or innovative solutions that could be implemented in the plant, or elsewhere. The studies included in the R&D tasks have a mid- to long-term perspective as they look towards the next phase of expansion of the processing train at the plant to include liquid fuel production and, in a more long-term perspective, consider implementation and exploitation of the technology on an industrial-scale, by targeting available fuel resources, thereby indicating the capacity of production in various locations.

The supporting R&D program encompasses studies and practical work on fuel drying, pelletisation and feeding against elevated pressure, as well as experimental studies of the gasification characteristics of a variety of biomass fuels, gas cleaning by state-of-the-art hot gas filters and catalytic upgrading of the gas by steam reforming of hydrocarbons, as well as innovative procedures using e.g. membranes. This supporting program also includes studies of the optimization of individual process steps, including the entire production chain from biomass to liquid fuel product, and an analysis by case studies of the feasibility for production of liquid fuels from biomass in terms of capacity and cost for various regions of Europe, as well as a study of socio-economic aspects.

CHRISGAS partners and funding

The partners in the CHRISGAS project are:
from Sweden: Växjö University, TPS Termiska Processer, Kungl Tekniska Högskolan (Royal Institute of Stockholm), Växjö Värnamo Biomass Gasification Centre, S.E.P. Scandinavian Energy Project, KS Ducente, Växjö Energi, Sydkraft
from Denmark: TK Energi
from Finland: Valutec
from Germany: Pall Schumacher, Forschungszentrum Jülich
from Greece: Helector
from Italy: Università di Bologna
from the Netherlands: TU Delft
from Spain: CIEMAT

The European Commission will support the CHRISGAS project with a grant of 9.5 million euro as part of its Framework 6 program. STEM (Swedish National Energy Agency) will contribute to the realization of WBGC as well as to financially support the CHRISGAS project.

Synthesis gas production

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 commercial process steps will 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, taking into account regional characteristics of fuel quality and quantity, three fuel production routes will be considered for this follow-up project:

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

The oil industry tends to favor the Fischer-Tropsch route as the products would be similar to conventional oil products. However, the DME/methanol route is another interesting option for the Värnamo plant.

As an example, the process scheme for the production of DME is shown in Figure 12.

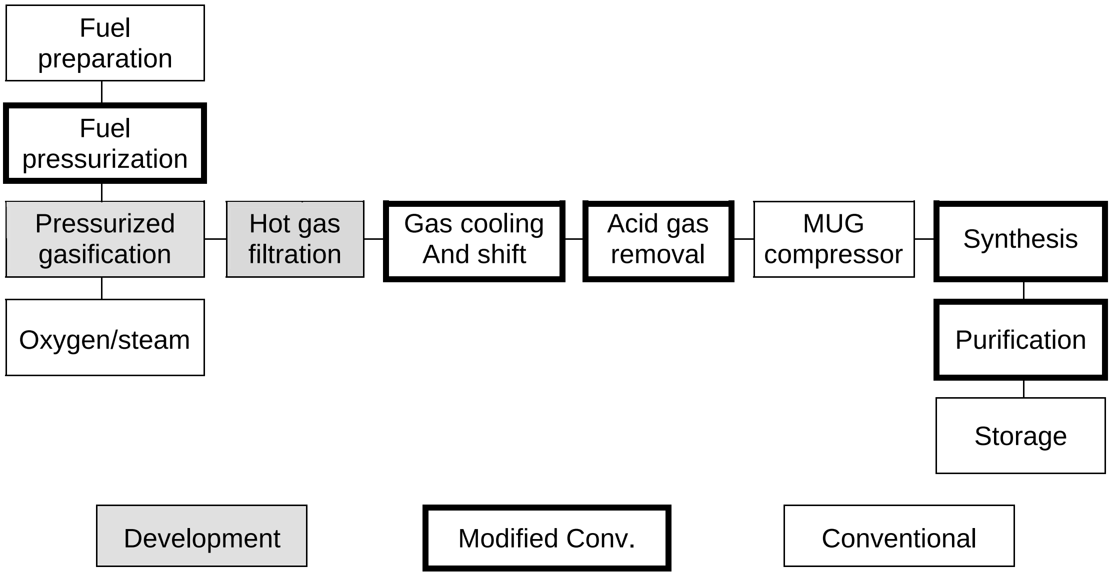

Figure 12: Typical flowsheet for a wood to biofuel plant

Major extensions to the plant at Värnamo to allow synthesis gas production are shown schematically in Figure 13. These include a system for the removal of acid gases, notably carbon dioxide from the raw synthesis gas, followed by compression of the gas to the level of synthesis processes of interest, i.e. 60-100 bar.

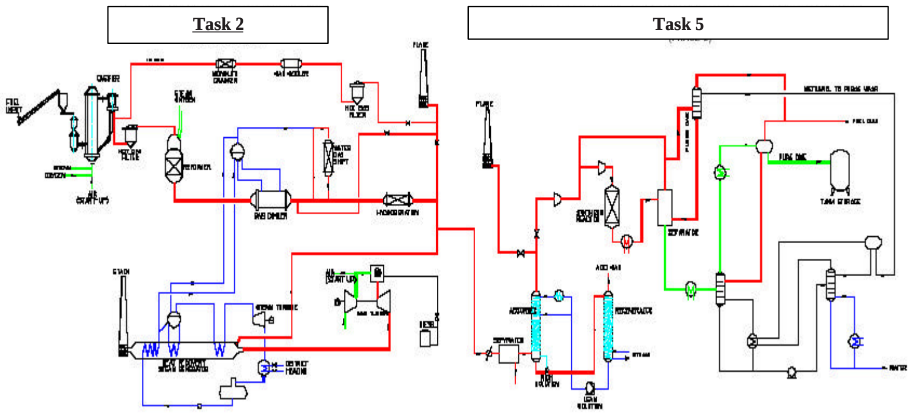

Figure 13: Phase II extension of the plant

There will be one or more synthesis sections to manufacture and upgrade fuels such as DME, methanol and Fischer–Tropsch diesel. The exact quantity of liquid fuel to be produced will be based on downstream requirements and the capacity of the reforming plant built. Furthermore, a PSA (pressure swing adsorption) facility to upgrade synthesis gas or purge gases to hydrogen fuel quality, or for use in fuel cells is also planned.

To complement the manufacturing facility, a tank farm will be installed containing several tanks for each product, such that e.g. off-spec. products can be handled without disturbance to the grade product. The installations will also include a vehicle filling station, as for these fuels, in particular DME and hydrogen, this is not fully tested and demonstrated elsewhere, and also a facility for filling a dedicated truck with DME for distribution needs for vehicle and fleet tests carried out outside the practical distance range of the Värnamo filling station.

9. CONCLUSIONS

The World must reduce the transport sector's dependence on oil. One way of achieving this reduction is to increase the use of vehicle fuels produced from renewables.

The primary objective of the CHRISGAS project is to demonstrate in the existing pressurized integrated gasification combined-cycle plant in Värnamo the manufacture of a hydrogen-rich gas from biomass. The demonstration part of the project consists of a number of tasks for which the objectives are:

- Conversion of several solid biofuels 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.
- 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.

Planning of the reconstruction of the Värnamo plant, in terms of the technical details, budget, etc. will be made in the first 18 months of the project and will be based partially on support from some parts of the supporting R&D program. Following this, plant construction will begin and when the plant is ready for operation in 2008, pilot plant test work shall commence.

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 will be conducted, the objectives of which include:

- Studies of the conditioning of the hydrogen-rich raw synthesis gas to the quality stipulated for synthesis gas suitable for manufacture of DME (di-methyl ether) or other potential products.
- Studies of the production of these fuels from various biofuels, at the scale and cost representative of typical biomass fuel chains in various regions in Europe.

Meeting the objectives of the CHRISGAS project will permit the reduction of greenhouse gases and pollutant emissions, increase the security of energy supplies and increase the use of renewable energy, as well as enhance the competitiveness of European industry and improving quality of life both within the EU and globally.

The CHRISGAS project will be part-financed by both the European Commission's Framework 6 programme and STEM.

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