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Drifterfarenheter från förgasningsanläggningar av biobränslen för kraftvärmeproduktion och industriella tillämpningar

Tomas Ekbohm, Erik Rensfelt, Eva-Katrin Lindman

**Drifterfarenheter från förgasningsanläggningar av
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industriella tillämpningar**

**Operating experiences of biomass gasification
plants for combined power and heat production
and industrial applications**

Tomas Ekbon
with contributions from:
Erik Rensfelt
Eva-Katrin Lindman

SYS 37553

Abstract

There is a large potential in biomass gasification, but the general knowledge is often low. The reason may be a limited number of commercial plants. The report gives a comprehensive up-to-date analysis of technologies and plants with operating experiences and availability. This enables a better basis for plant investors to assess the competitiveness of gasification technology for new technology investments.

There is strong evidence that one-step gasifiers without further gas cleaning can be reliable with the availability approaching 100%. The more advanced technologies have had troublesome experience but can reach 80-85% or higher. There is a great wealth of operating knowledge at these plants which should be considered for a sequential plant of same gasification technology to secure the knowledge transfer.

Sammanfattning

Introduktion

Förgasning innebär en omvandling av ett fast eller flytande (gasformigt kan också gälla) material till en gas genom partiell oxidation med luft / syre eller ånga med separat tillförsel av värme. Partiell oxidation uppnås genom att begränsa tillförseln av en oxidant, normalt luft, ånga eller koncentrerat syre (eller en kombination). För organiskt baserade råmaterial är den resulterande gasen typiskt en blandning av kolmonoxid, koldioxid, väte, metan, vatten, kväve och små mängder av högre kolväten. Dock kommer gasen att även innehålla tjära och partiklar etc, som kan behöva tas bort innan gasen är lämplig för förbränning. Variationsgraden i gassammansättningen beror på vilken förgasningsteknik som används.

Förgasningstekniken med biomassa har varit kommersiell i årtionden, men inte hittills vitt spridd i Europa. Ändå kan förgasning av biomassa integrerad med kombi-cykel ge en hög verkningsgrad och många fördelar i samledning i en panna. Det finns nu omfattande forskning och utveckling av mer avancerad förgasningsteknik på nationell och internationell nivå för högeffektiva koncept, som innebär syntes till fordonsbränsleprodukter och kemikalier med höga produktvärden.

Det finns en stor trädbränslepotential vilken kan användas med förgasning till att ge flertal högvärdiga produkter. Den allmänna kunskapen inom energibranschen om förgasningsteknik är dock ofta låg, vilket kan bero på det begränsade antal kommersiella anläggningar som har byggts. Det finns många variabler vid investeringsbeslut att ta hänsyn till. I allmänhet ger bränslekostnader och produktpriser med investerings- och produktionskostnad en grundläggande kalkyl om anläggningsekonomi, vilka är tillgängliga från en leverantör. Dock är anläggningens tillgänglighet kanske ett av de områden som är mest kritiska i alla anläggningar vilket påverkar chanserna för ett investeringsbeslut, och det är uppgifter som inte är lätt att få från leverantörerna eller från publika rapporter.

Mål och syfte

Det finns många studier som har undersökt förgasning av biomassa. Men det finns inga heltäckande sammanställningar av detaljerade drifterfarenheter och tillgängligheter på de förgasningsanläggningar som byggts och som har varit i drift sedan 1980-talet. Därför finns det ett behov av en omfattande studie som beskriver operativa erfarenheter och tillgänglighet av ett antal förgasningsanläggningar. Projektet omfattar en sammanställning och analys av gjorda drifterfarenheter med målet att bredda kunskapsbasen och möjliggöra ett bättre underlag för investerare att bedöma konkurrenskraften hos förgasningsteknik för nya teknikinvesteringar. En mycket viktig informationskälla har varit IEA Bioenergy Task 33 med work shops och rapporter som har sammanfattande uppdateringar av förgasningsprojekt och anläggningar. Det övergripande målet med projektet är att öka kunskapen om drifterfarenheter vid primärt befintlig förgasning till kraftvärme och industriella applikationer. Vidare syftar projektet till att undersöka konkurrenskraften för förgasning, och för- och nackdelar med de olika teknikerna.

Studerade teknologier och anläggningar

Denna rapport redovisar drifterfarenheter av förgasning av biomassa med både intervjuer och studiebesök för utvalda anläggningar och teknikleverantörer. Urvalet har gjorts för att inkludera olika relevanta förgasningstekniker med fast bädd och fluidiserad bädd och suspensionsreaktorer. Studien har omfattat ledande företag och kommersiella anläggningar som idag är i drift eller är stängda, men som har gett viktiga erfarenheter vilka är värdefulla för en djupare förståelse. Fokus är inte att lyfta fram brister i sig av förgasning av biomassa utan snarare att analysera de områden som är och har varit utmanande och med de lösningar som har följt.

De utvalda anläggningarna (primärt kommersiella, och ej forskningsreaktorer) sträcker sig från små- till storskaliga och teknik från låg komplexitet med begränsad gasrening till hög komplexitet i bioraffinaderi med djupgasrening. Slutsatserna och lärdomarna är generella och viktiga inom varje kategori. Sammanfattningsvis innehåller den här rapporten en up-to-date analys av drifterfarenheter av förgasning med utvalda anläggningar för att representera den använda tekniken. En del anläggningar har varit i drift under många år och en ny modern anläggning skulle få mycket bättre anläggningsprestanda och de beskrivna första typerna av anläggningar bör inte betraktas som state-of-the-art som sådana.

Diskussion och analys

Trots att det finns gott om förgasare runt om i världen, där de flesta av dem är kolbaserade har förgasning av biomassa i princip blivit kommersiellt tillgänglig endast de senaste fem åren. Undantagen är CFB mesaugnsförgasare och fastbäddsförgasare som Bioneer med teknik från 1980-talet. Detta är ett starkt bevis för att en-stegsförgasare utan ytterligare gasrening kan vara tillförlitliga och driftstartas ganska snabbt även med helautomatisk drift. Erfarenheterna med flerstegsprocesser med avancerad gasrening illustrerar att detta är mycket svårare och kräver mer tid och pengar för driftsättning. Även när den kompletta tekniken har visats på pilotanläggningar under mycket lång tid, finns det fortfarande många kostnader som kommer att behövas tas. Med denna bakgrund kan endast långsiktiga aktörer med stora budgetar ta risken. Avfallsförgasning innehåller en hel del hanteringsproblem, och de flesta av de kända förgasningsproblemen. Enerkem-tekniken tar just nu steget till kommersiell skala baserad på pilot- och demonstrationserfarenheter. Detta pekar på det faktum att teknikutvecklingen till kommersiell skala endast till en mindre del är teknikbaserad.

Kommersiellt perspektiv

En trolig orsak till att det saknas en stor utbredning av förgasningsteknik, trots stora investeringar i forskning, utveckling och demonstration, är att det finns ett begränsat antal kommersiella referensanläggningar. Drifterfarenheterna är något sämre jämfört med konventionell teknik i många fall, även om det finns viktiga undantag. Tillräcklig kunskapsbas är hittills nästan icke-existerande för en rättvis bedömning av tillgänglighet, robusthet och underhållskostnader. Den beräknade drifttillgängligheten är av yttersta vikt vid utvärdering olika teknikalternativ. Värdet av en inkrementell verkningsgradhöjning minskar inom loppet av bara några dagar vid bortfallet av en baslast- eller medellastreaktor. När tekniken är helt mogen, är det möjligt att minska både investerings- och drift- samt underhållskostnader betydligt.

Konventionell bibränslebaserad småskalig förbränning och ångturbin (Rankine-cykeln) kan i bästa fall nå en elektrisk verkningsgrad på cirka 25 % (netto), och det är mycket svårt att få ett betydande högre elutbyte. Å andra sidan har förgasning av biomassa och förbränning i gasmotorer rapporterat elutbyten på 25-35 %. Flera teoretiska studier har visat att en produktion baserad på trycksatt förgasning av cirka 150 MW tillfört träbränsle integrerad med en kombicycle kan nå ett netto elutbyte på 43-44 % vid full kraftvärmedrift och kondensdrift vid 46-48 %, jämfört med ångturbinconcept utrustad med överhettning för ett elutbyte om 32-33 %.

Slutsatser

Anläggningens tillgänglighet är av stor betydelse för en förgasningsanläggning, inte bara för att hålla ett positivt kassaflöde för anläggningen men också för förgasningsteknologi som sådan att konkurrera med andra teknologier i investeringar för nya produktionsanläggningar. Av de studerade teknologier och anläggningar som analyserats har några valts ut och ges i nedan tabell med respektive anläggnings drifttillgänglighet. En jämförelse görs med normala drifttimmar per år för att fastställa anläggningens tillgänglighet för första 12 månader och den totala drifttillgängligheten hittills samt det senaste värdet. Det ackumulerade antalet drifttimmar ges också.

Tabell 1. Sammanfattning av drifttillgängligheter för valda anläggningar, från Bilaga A.

Projekt / verk	Process	Normal	Första 12 mån	Tillgänglighet	Dagens tillgäng.	Ackumulerade timmar
Värö	CFB	8300 h?	Data saknas	Data saknas	Data saknas	>90 000 h
Bioneer	Updraft	8000 h	Data saknas	>99 %	>99 %	200 000 h på varje förgasare
Harboöre	Updraft	8000 h	Data saknas	>95 %	97 % förgasare, 95 % motor	150 000 h förgasare, 65 000 h per motor
Kymenjärvi I	CFB	7000 h	Data saknas	98 %	96-99 %	27 000 h
Corenso	CFB	Data saknas	Data saknas	90-95 %	90-95 %	23 000 h (dec. 2005)
Güssing	FICFB	7500 h	3200 h förgasare, 1300 h motor	>7000 h = 93 %	7700 h (2012)	>80 000 h förgasare, >80 000 h motor
Skive	BFB	(+90 % för ny anl.)	(+80 % för ny anläggning.)	70-80 %	80-90 %	20 000 h
Oberwart	FICFB	7500 h	1530 h = 20 %	82 % (mål 86 %)	7500 h	26 200 till dec. 2013
Westbury	BFB	8000 h (design)	Data saknas	Data saknas	95-96 %	+5000 h
Varkaus	CFB	4740 h (beräknat)	94.3 % förgasare 47.2 % sidoström	70 % (medel)	96 % förgasare 93 % sidoström	Förgasare 9000 h, Gasrening 5500 h
Hortlax	VIPP	8000 h, >85 %	<5 %, mycket lågt	<5 %, mycket lågt	Rapporterat som bra	Ett hundratal timmar
Vaasa	CFB	6500 h	97 %, 5000 h (första säsong)	98 %	99 %	>9000 h
Gobigas I	FICFB	8000 h	2400 h första 12 månader??	Data saknas	Data saknas	>1200 timmar (okt. 2014)

Tabellen ger att det skiljer oerhört mellan teknologier för de första 12 månadernas drift för dessa anläggningar. För ny teknik som ska kommersiellt demonstreras (t.ex. fluidiserad bädd med avancerad gasrening) eller en uppskalad anläggning, annan tillämpning eller integrerad kan tillgängligheten första drifttiden antas bli mycket låg, troligen under 40 %. För känd teknologi (t.ex. fastbäddsförgasare med avancerad gasrening) kan tillgängligheten antas att bli mycket hög, närmare 100 %, och ligga kvar på denna nivå.

Flera av de kommersiella demonstrationsanläggningarna har visat på besvärliga första driftår och efter några år har tillgängligheten varit acceptabel i intervallet 80-85 % och för några även >95 %. Således har alla förgasningsteknologier kunnat nå väldigt höga siffror när erfarenheter och investeringar gjorts för att korrigera svårigheter i processerna vilket get driftstopp. Slutsatsen är att det finns en stor mängd kunskap på dessa anläggningar vilket är av stor vikt att tas med när en nästa anläggning ska byggas för att säkra kunskapsöverföring.

Denna rapport bygger på diskussioner med anläggningsoperatörer och deras drifterfarenheter med heterogena bränslen för integrerade processer vid höga temperaturer och efterföljande gasrening. Det finns värdefulla lärdomar och rapportens rekommendationer kan ge betydande kostnadsbesparingar för förbättrade koncept men de beror också starkt på vald teknologi med tillämpning samt bränsle(n).

Nyckelord: biomassa, förgasning, gasrening, drifttillgänglighet

Summary

Introduction

Gasification is the conversion of a solid or liquid (gaseous may also apply) feedstock into a gas by partial oxidation with air/oxygen or steam with separate supply of heat. Partial oxidation is achieved by restricting the supply of oxidant, normally air, steam or concentrated oxygen (or combination). For organic based feedstock's, the resultant gas is typically a mixture of carbon monoxide, carbon dioxide, hydrogen, methane, water, nitrogen and small amounts of higher hydrocarbons. However, the gas will contain tars and particulate matter, which may need to be removed before the gas is suitable for combustion. The degree of this variation in gas composition will depend on the gasification technology used.

The technology of biomass gasification has been commercial for decades, however, not widely deployed in Europe so far. Still, biomass gasification integrated with combined cycle may yield high power yields and many benefits in co-firing in a boiler. There is now an extensive research and development of more advanced gasification technologies at national and international level to high-performance concepts, involving synthesis to automotive fuel products and high-value chemicals.

There is a large potential of wood fuels which can be used with gasification for multitude of high-value products. However, the general knowledge in the energy industry of the gasification technology is often low, which may arise from the limited number of commercial plants been built. There are many variables to account for in an investment decision. In general, fuel costs and product prices with capital investment cost and production cost will give basic economic information about the economic performance, which are all available from a process plant supplier or contractor. However, the plant availability is perhaps one of the most critical areas in any plant affecting the chances for an investment decision, and which is not easily obtainable from plant and process suppliers or public data.

Goal and objective

There are many studies which investigate biomass gasification. However, there are no comprehensive compilations, of detailed operating experiences and the availabilities of the biomass gasification plants built and which have been in operation since the 1980s. Hence, there is a need for a comprehensive study which details the operational experiences and availability of a number of biomass gasification plants to survey the performance. The project comprise a compilation and analysis of made operating experiences with the goal to broaden the knowledge base and enable a better basis for plant investors to assess the competitiveness of gasification technology for new technology investments. A most important source of information has been the IEA Bioenergy Task 33 with work shops and the country reports which have summary updates of biomass gasification activities, projects and plants. The overall objective of the project is to increase knowledge of operating experience at primary existing gasification CHP and industrial applications. Furthermore, the project aims to investigate the competitiveness of gasification, the advantages and disadvantages of the different technologies.

Studied technologies and plants

This report details the operating experience of biomass gasification with both interviews and study visits to selected plants and technology suppliers. The selection has been made to include different relevant biomass gasification technologies including fixed-bed and fluidized-bed and entrained-flow gasification reactors. The study has involved leading companies and plants which are today in operation or have been shutdown but with important experience that is valuable for a deeper understanding. The focus is not to highlight shortcomings *per se* of the biomass gasification technology but rather to analyse the areas which are and have been challenging and with the solutions that have followed.

The selected plants range small-scale to large-scale and the technologies are different from low complexity with limited gas cleaning to high complexity in biorefinery mode with deep gas cleaning. Therefore, the conclusions and lessons learned are general and important in same category. Still, the conclusions for the overall gasification technologies are made for future investments and developments. In summary, this report includes an up-to-date analysis of the operating experience of gasification with selected plants to represent the used technology. As some plants have been in operation for many years a new modern plant would have far better plant performance and the described first-of-a-kind plants should not be regarded as the state-of-the-art as such.

Discussion and analysis

Despite the fact that there are plenty of gasifiers around the world, most of them are coal based while the biomass gasification systems from small to large are commercially available only in last five years. The exceptions are CFB limekiln gasifiers and fix-bed updraft Bioneer gasification technology from the 1980s. This is a strong evidence that one-step gasifiers without further gas cleaning can be reliable and rather quickly started up even with fully automatic operation. The experience with multistep processes with advanced gas cleaning illustrate that this is much more difficult and needs more time and money for commissioning. Even when the complete technology has been demonstrated at pilot plant scale for a very long time, there are still many costs still to be taken. With this background only long-term players with big budgets can take the risk. Waste gasification includes a lot of handling problems, permissions problems and most of the known gasification problems. The Enerkem technology is just now taking the step to commercial scale based on pilot and demonstration experience. That points to the fact that technology development to commercial scale only to a minor part is technology based.

Commercial perspectives

One plausible reason for the lack of a major impact of gasification technology, despite major investments in research, development and demonstration, is the limited number of commercial reference plants. Operational experience is somewhat poor compared to conventional technology in many cases, although there are important exceptions. Sufficient knowledge basis are so far almost non-existing for a fair assessment of the availability, durability and maintenance costs. The estimated operating availability is of utmost importance when evaluating different technology alternatives.

The value of an incremental power yield gain is diminished in a matter of only a few days unavailability of a base-load or medium-load reactor. Once the technology is fully mature, it is possible to reduce both investment and operation and maintenance costs significantly.

Conventional biomass-based small-scale combustion and steam turbine (Rankine cycle) may at best reach net electrical efficiency of some 25%, and it is very difficult to obtain a substantial higher power yield. On the other hand, biomass gasification and combustion in gas engine concepts have reported power yields ranging 25-35%. Several theoretical studies have shown that production based on pressurized gasification of some 150 MW wood fuel input integrated with a combined cycle could reach a net electrical efficiency of 43-44% by full CHP operation and condensing operation at 46-48%, compared with cogeneration steam turbine cycle concept equipped with re-heat for a power yield of 32-33%.

Conclusions

The plant operation availability is of great importance for a gasification plant, not only to keep plant economics positive but also for gasification technology as such to compete with other technologies in investments for new production plants. The technologies and plants studied have been analysed and some selected plants are given in below Table with the respective plant operating availabilities. A comparison is made with the normal operating hours per year to establish the plant availability for the first 12 months of operation and the total availability to date and the current or recent plant availability. Last the accumulated equivalent operating hours are given.

Table 1. Summary of selected gasification plant operating availabilities, from Appendix A.

Project/plant	Process	Normal	First 12 months	Tot avail.	Current avail.	Accumulated hours
Värö	CFB	8300 h?	No data	No data	No data	>90 000 h
Bioneer	Updraft	8000 h	No data	>99%	>99%	200 000 h on each gasifier
Harboöre	Updraft	8000 h	No data	>95%	97% gasifier, 95% engine	150 000 h gasifier, 65 000 h per engine
Kymenjärvi I	CFB	7000 h	No data	98%	96-99%	27 000 h
Corenso	CFB	No data	No data	90-95%	90-95%	23 000 h (Dec. 2005)
Güssing	FICFB	7500 h	3200 h gasifier, 1300 h engine	>7000 h = 93%	7700 h (2012)	>80 000 h gasifier, >80 000 h engine
Skive	BFB	(+90% for new plant)	(+80% for new plant)	70-80%	80-90%	20 000 h
Oberwart	FICFB	7500 h	1530 h = 20%	82% (goal 86%)	7500 h	26 200 until Dec. 2013
Westbury	BFB	8000 h (design)	No data	No data	95-96%	+5000 h
Varkaus	CFB	4740 h (calc from %)	94.3% gasifier 47.2% slipstream	70% (average)	96% gasifier 93% slipstream	Gasifier 9000 h, Gas cleaning 5500 h
Hortlax	VIPP	8000 h, >85%	<5%, very low	<5%, very low	Reported as good	A few hundred hours
Vaasa	CFB	6500 h	97%, 5000 h (first season)	98%	99%	>9000 h
Gobigas I	FICFB	8000 h	2400 h first 12 months??	No data	No data	>1200 h (Oct. 2014)

It can be seen that the first 12 months of operation for these plants differs extremely between technologies. For a new technology to be commercially demonstrated (e.g. fluidized-bed with advanced gas cleaning) or a plant with difference in scale, application or integration the availability can be assumed to be very low, most possibly below 40%. For well-known technologies (e.g. fixed-bed gasifiers with limited cleaning) the availability can be assumed to be very high, approaching 100%, and remain at this level. For the commercial demonstration plants the records have shown several first years of troublesome operation and after a few years the availability has been acceptable in the range of 80-85% and for a couple even >95%. Thus, all gasification technologies have shown to reach very high numbers given that the lessons are learned and investments are made to correct process difficulties that emanate plant outages. The conclusion is that there is a great wealth of operating knowledge at these plants which should be considered for a sequential plant of same gasification technology to secure the knowledge transfer.

This report is based on discussions with plant operators and the learned experience to operate several processes and heterogen fuels at high temperatures and to clean the product gas. There are valuable lessons learned and these recommendations may give considerable cost savings for improved concepts but they also depend heavily on selected technologies with applications and fuel(s).

Keywords: biomass, gasification, gas cleaning, plant availability

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1 Introduction

1.1 Background

Gasification is the conversion of a solid or liquid (gaseous may also apply) feedstock into a gas by partial oxidation with air/oxygen or steam with separate supply of heat. Partial oxidation is achieved by restricting the supply of oxidant, normally air, steam or concentrated oxygen (or combination).

For organic based feedstock's, the resultant gas is typically a mixture of carbon monoxide, carbon dioxide, hydrogen, methane, water, nitrogen and small amounts of higher hydrocarbons. However, the gas will contain tars and particulate matter, which may need to be removed before the gas is suitable for combustion. The degree of this variation in gas composition will depend on the gasification technology used.

The technology of biomass gasification has been commercial for decades, however, not widely deployed in Europe so far. Still, biomass gasification integrated with combined cycle may yield high power yields and many benefits in co-firing in a boiler. There is now an extensive research and development of more advanced gasification technologies at national and international level to high-performance concepts, involving synthesis to automotive fuel products and high-value chemicals.

The forest products and pulp & paper industry, as well as the energy industry are today the most dominant players in terms of usage and consumption of forest products and fuels. Meanwhile, there is a large potential of wood fuels which can be used with gasification for multitude of high-value products. However, the general knowledge in the energy industry of the gasification technology is often low, which may arise from the limited number of commercial plants been built.

Electricity and heat can be produced from many types of fuels with many different technologies and concepts. There are therefore many variables to account for, and consequently gives no easy decision for an investment decision. In general, fuel costs and product prices with capital investment cost and production cost will give basic economic information about the economic performance, which are all available from a process plant supplier or contractor.

However, the plant availability is perhaps one of the most critical areas in any plant affecting the chances for an investment decision, and which is not easily obtainable from plant and process suppliers or public data. Hence, there is a need for a comprehensive study which details the operational experiences and availability of a number of biomass gasification plants to survey what the performance has been and what can be expected from a modern biomass gasification plant.

1.2 Studies and reports

There are a few Swedish studies within Värmeforsk and Elforsk which investigate new heat and power production based on biomass gasification. However, there are no comprehensive compilations, of detailed operating experiences and the availabilities of the biomass gasification plants built and which have been in operation since the 1980s.

The most relevant Swedish studies of biomass gasification for further reading of the technology, process design and energy efficiency are the following:

- Björn Kjellström, *Cost of electricity from small scale co-generation of electricity and heat*, report 1237, Värmeforsk, July 2012.
- Olle Nyström, Per-Axel Nilsson, Clas Ekström, Anna-Maria Wiberg, Bengt Ridell, David Vinberg, *Electricity from new and future facilities 2011*, Summary report, Elforsk report 11:26, May 2011.
- Jennie Rodin and Olle Wennberg, *Gasification for fuel production in large and small scale polygeneration plants*, report 1150, Värmeforsk, Feb 2010.
- Lars Waldheim, Eva K. Larsson, *Scanning of future electricity and heat technologies, Progress report gasification with gas turbine / engine for cogeneration*, Elforsk report 08:78, December 2008.
- Olle Nyström, Kent Johansson, Pontus Stein Wall, *Small-scale bio fuelled heat and power requirements for standardized technical and fuel solutions from a systems perspective*, Report 715, Värmeforsk, Jan. 2001.

Then, the Swedish Gas Centre has published two reports (No. 232 and 240) about biomass gasification technologies which are relevant for this study. Other references are given in the respective chapter.

A most important source of information has been the IEA Bioenergy Task 33 with work shops and the country reports which have summary updates of biomass gasification activities, projects and plants. The 2012 year country report authored by Lars Waldheim of Waldheim Consulting has been used in this report about Swedish gasification plants, foremost Värnamo and Värö and in the Appendix about TPS.

1.3 Goal and objective

Biomass gasification technology can produce a very clean, process and fuel gas, which can potentially provide very good environmental performance and high flexibility in applications. The project comprise a compilation and analysis of made operating experiences with the goal to broaden the knowledge base and enable a better basis for plant investors to assess the competitiveness of gasification technology for new technology investments.

The study focuses on the gasification system for combined heat and power production. However, in some cases there is gasification in the forest industry for heat production with very limited gas cleaning. Operating experience with gas cleaning will therefore include also pilot plants to provide the necessary information.

The overall objective of the project is to increase knowledge of operating experience at primary existing gasification CHP and industrial applications. Furthermore, the project aims to investigate the competitiveness of gasification, the advantages and disadvantages of the different technologies. The project comprises more specifically the following work packages:

1. A summary description of the various gasification technologies with built facilities (mainly Scandinavia) as well as state-of-the-art with today's contractors and developers. This provides a basis for understanding the operating experience.
2. Study visits and interviews of selected gasification plants with investigation of made operational experience with first year and total availability discussing areas of fuels, materials, equipment, process technology, performance, emissions, etc.
3. Analysis and evaluation of made operational experiences for future plant owners for the expected availability of the various technologies and how to prevent and avoid or minimize operational problems with various process solutions and possible cost savings which can be done to improve the plant economy.

1.4 Survey design basis

This report details the operating experience of biomass gasification with both interviews and study visits to *selected* plants and technology suppliers. The selection has been made to include different relevant biomass gasification technologies including fixed-bed and fluidized-bed and entrained-flow gasification reactors.

The study has involved leading companies and plants which are today in operation or have been shutdown but with important experience that is valuable for a deeper understanding. The focus is not to highlight shortcomings *per se* of the biomass gasification technology but rather to analyse the areas which are and have been challenging and with the solutions that have followed.

The selected plants range small-scale to large-scale and the technologies are different from low complexity with limited gas cleaning to high complexity in biorefinery mode with deep gas cleaning. Therefore, the conclusions and lessons learned are general and important in same category. Still, the conclusions for the overall gasification technologies are made for future investments and developments.

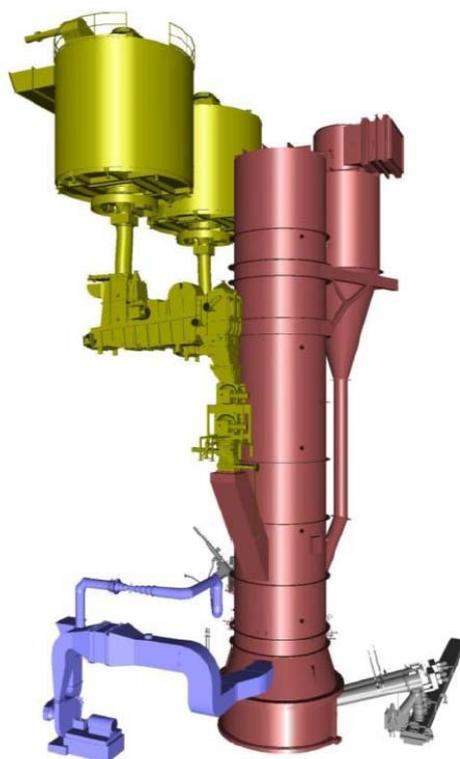
In summary, this report includes an up-to-date analysis of the operating experience of gasification with selected plants to represent the used technology. As some plants have been in operation for many years a new modern plant would have far better plant performance and the described first-of-a-kind plants should not be regarded as the state-of-the-art as such.

Definition of units: Wherever the unit MWf is used it is referred to the capacity of the fuel input to the gasifier, not the capacity of the energy capacity from the gasifier unit.

2 Biomass gasification technologies

2.1 Introduction

Gasification have been successfully utilized in all kind of applications, mainly in the oil and chemical industries, and considered as commercial technology for over 60 years. Regarding biomass gasification, successful commercial operation of CFB gasifiers coupled to lime kilns was achieved during the 1980s and they accumulated considerable amount of operational hours but with very limited gas cleaning installed, only hot cyclones.

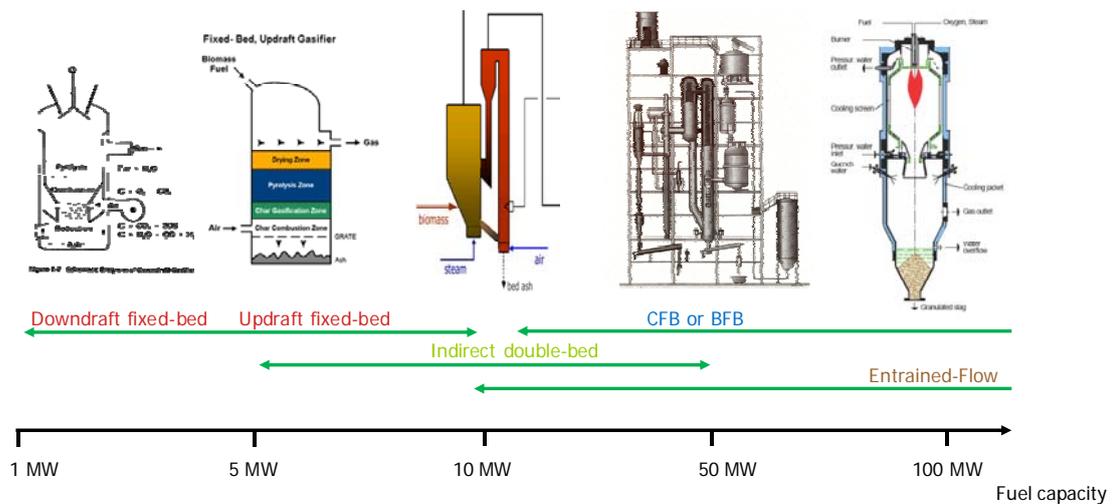


Figur 1. Schematisk bild av CFB förgasaren (Ref. Valmet)

Figure 1. Schematic of a CFB gasifier reactor unit (Ref. Valmet).

During the same period several pilot plants were built and some operated at elevated pressure and were oxygen-blown for synthesis gas purposes. Some were operated with technical success as the Mino pilot plant at Studsvik, Sweden and the HTW pilot plant in Germany and later in Oulo, Finland at commercial scale (with peat/sawdust).

Despite the reasonable technical success that development came to a complete stop due to lower oil prices that made it impossible to compete with liquid fuels from biomass. When developers looked at other more near-term possibilities for biomass gasification the electricity market drew the attention. Different technologies looked promising depending on scale (see Figure below).



Figur 2. Olika förgasningsreaktorer vid indikativa skalstorlekar.

Figure 2. Different gasification reactor technologies at indicative different scales.

Most developers chose to develop atmospheric gas cleaning to couple to gas or dual fuel engines and in a few cases to gas turbines. Only one, Bioflow (Sydkraft/Ahlström) developed pressurized air blown gasification with high temperature dust clean-up to demonstration-scale including integration with a gas turbine during the 1990s. The demonstration plant in Värnamo achieved good results after some initial problems.

In Finland, Carbona (now Andritz) developed pressurized fluidised bed gasification up to demonstration-scale but not including a gas turbine. The engine based biomass gasification market developed slowly and the gas cleaning efforts had problems in many small scale engine projects.

From 1995 the international community, USA and EU pushed for BIGCC but the launched projects and subsidy schemes scared most developers away after initial pilot test and feasibility studies. The engine-based demonstrations projects were built in a few plants: e.g. at Skive with Carbona, at Güssing with Repotec and at Kokemäki with Novel. These plants included gas cleaning schemes that can be applied also to gas turbines. A modern turbocharged engine has almost the same requirements as a gas turbine but only with lower feed pressure.

Foster Wheeler built in 1998 a 50 MWf gasification plant in Lahti at the Lahti power plant which used an atmospheric CFB gasifier fuelled by wet biomass to produce a very low-calorific value gas co-fired in an existing coal-fired boiler. The accumulated biomass fuel was 400 000 tonnes and an operating experience of 27 000 h.

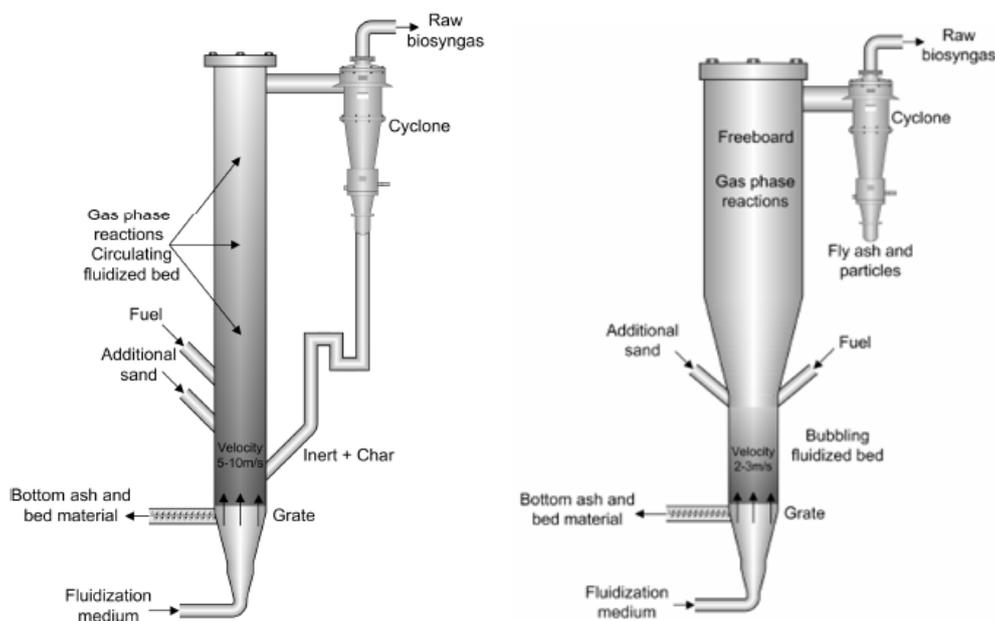
From the perspective back in 1990, atmospheric gasification with tar cracking seemed very promising with pilot experience and commercial experience from the lime kiln gasifier. Feeding problems seemed easier to overcome at atmospheric pressure.

After 2005 most of the rapidly growing interest is related to transportation fuels at large scale. The current trend is simultaneous biomass gasification development for three markets and applications of the product gas, co-firing with less gas clean-up (e.g. pulp industry), integration with gas engines (or gas turbines) with moderate gas clean-up and (combined heat and power industry) syngas production for synthesis of transportation fuels (oil & petrochemical industry) with deep gas cleaning and conditioning.

2.2 Studied technologies and plants

Basically, there are two main gasification categories which are relevant for this report, direct gasification using oxygen/steam as oxidant and in-direct gasification using generally external heat and steam as oxidant.

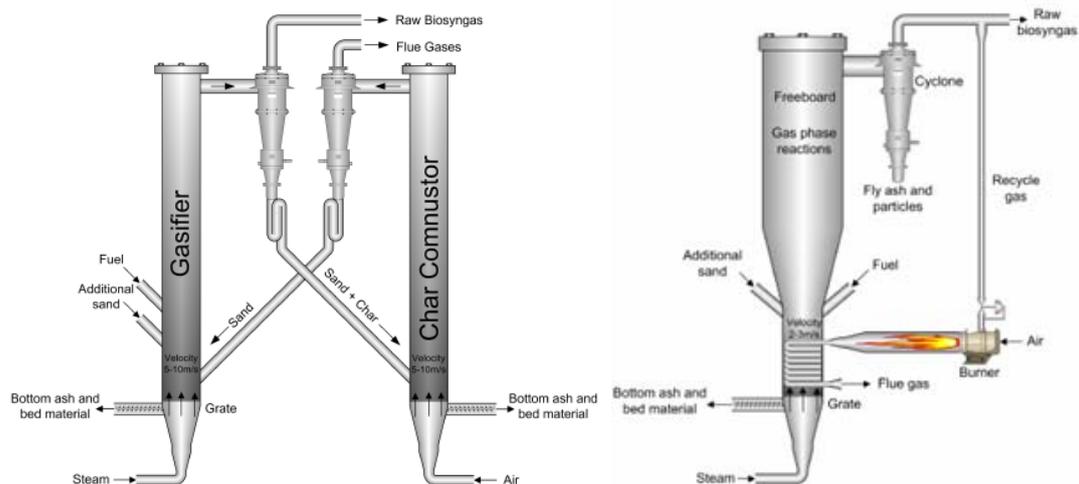
In addition to these categories, there are two main reactor types, the bed reactor (fixed and fluidised) and the entrained-flow reactor. Moreover, there are two main fluidised-bed reactor types, the circulating (CFB) and the bubbling (BFB) fluidised-bed, see Figure. This technology lends much experience from CHP applications and has advantages with fuel flexibility, possibility for pressurised conditions, less complex and producing a gas suitable for many applications.



Figur 3. Schematiskt på CFB- och BFB-reaktorer, vänster till höger (Ref. Umeå Universitet).

Figure 3. Schematic of CFB and BFB gasifier reactors, left to right (Ref. Umeå University).

The alternative, the indirectly heated fluidised-bed produces a medium value product gas without the need for a costly and power-consuming separate oxygen unit, which is needed with direct gasification to obtain same calorific value of the produced gas. In addition to these, there are many other biomass gasification concepts for mainly heat and power production, which are in different stages of commercialization.



Figur 4. Schematiskt på Forced Internal Circulating Fluidised Bed (FICFB) med dubbelreaktorer, jämfört med en enstegsreaktor baserad på ångreformering, vänster till höger (Ref. Umeå Universitet).

Figure 4. Schematic of Forced Internal Circulating Fluidised Bed (FICFB) with twin reactors compared with single stage gasifier reactor based on steam reforming, from left to right (Ref. Umeå Universitet).

In this project, the experiences of biomass gasification has been investigated and evaluated with both study visits and telephone and physical meeting interviews. The plants have either been with a dedicated biomass fuel like pellets or with a mixture of different biomass types.

The technologies have comprised direct-heated fluidised beds (CFB and BFB), in-direct heated double fluidised bed, fixed beds and cyclone gasification, which essentially covers the more relevant technologies and plants which have accumulated longer operational experience. The plants visited and companies are further detailed in following chapters.

For a detailed plant data table with technical features of all the plants, see Appendix A.

In addition, please see Appendix B for gas compositions for each plant studied.

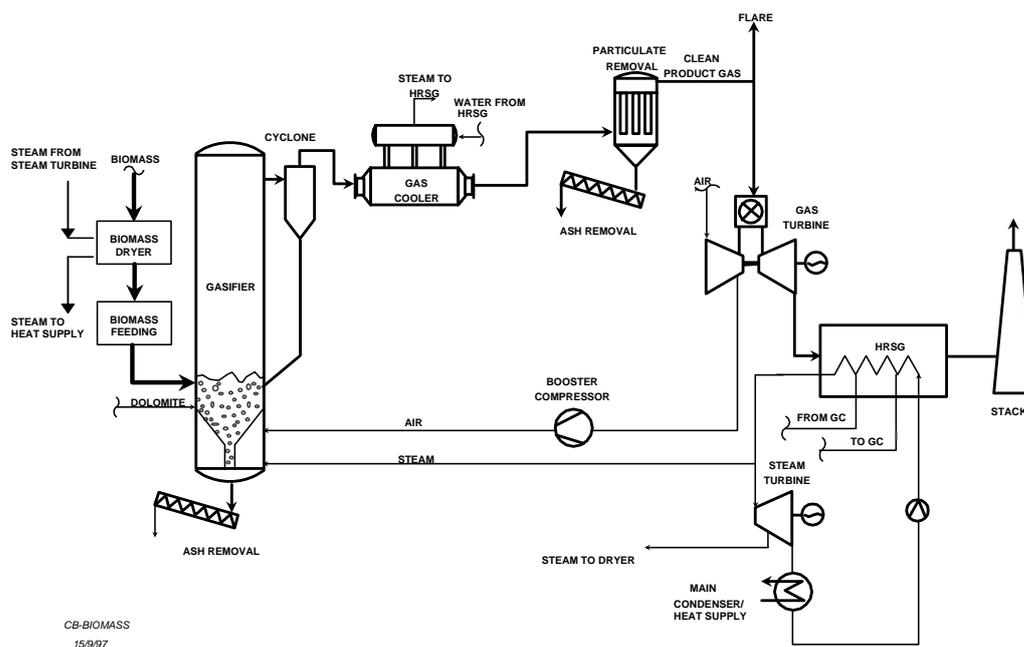
3 Andritz

3.1 Background

Carbona is a biomass gasification technology based company supplying plants for various applications. Andritz Oy (Finnish subsidiary of Austrian based Andritz Group) acquired ownership in Carbona Inc. gradually from 2006. As of 1 Sept 2014 Carbona Oy has merged completely into Andritz.

Andritz is one of the leading suppliers in pulp & paper industry and has also biomass CFB gasification background from 1980s as Ahlstrom Machinery Oy, Pyroflow. Carbona has developed BFB biomass gasification technology since 1996. Andritz Carbona now offers plants, for both BFB and CFB gasification technologies.

The gasification plant includes fuel handling, drying, feeding, gasification and gas clean-up. The fuel handling process is a conventional process including storage, conveying, chipping and sieving equipment specifically designed for the different biomass fuel types. See below Figure for a schematic.



Figur 5. Schematiskt på BIGCC processen (Ref. Andritz)

Figure 5. Schematic of BIGCC process plant (Ref. Andritz).

The range and scales of offered biomass gasification technologies are depicted in below Figure. The relevant technology is for syngas production with oxygen-blown pressurised BFB gasification which is developing to commercial readiness as of today.

Fuel gas for kilns	(Co-)firing (boiler)	Co-generation (gas engine)	IGCC (gas turbine)	Syngas production
<ul style="list-style-type: none"> 10-100 MWth. Atmospheric CFB (circulating fluidized bed) Fossil fuel replacement 	<ul style="list-style-type: none"> 10-150 MWth. Atmospheric CFB Power by steam cycle 	<ul style="list-style-type: none"> 10-50 MWth. Low pressure BFB (bubbling fluidized bed) Power by gas engine units 	<ul style="list-style-type: none"> 30-150MWth. Pressurized BFB (air blown) Power by gas/steam turbines 	<ul style="list-style-type: none"> 150 MWth/unit Pressurized BFB (oxygen blown) Development phase
Pulp and paper and cement industries	Utilities and all industries with large fossil fuel fired boilers	Municipal utilities	New mid-size power plants with max power	BTL producers (P&P & others) and utilities
				
Fuel gas	Green power	Green power	Green power	Bio liquids

Figur 6. Bredd på biomassaförgasning (Ref. Andritz).

Figure 6. Range of biomass gasification technologies (Ref. Andritz).

The basis for Andritz technology development started by GTI in the 1980s with the pilot plant in Chicago which continued in Tampere with a 100 tonnes per day, 15-18 MWf gasifier where 5900 tonnes of different fuels had been gasified for a total of 3700 hours until it was mothballed in early 2000s. The fuels included wood chips, paper and forestry residues, salix, straw, alfalfa, and coal/biomass mixtures. The development continued with the 30 MWf Skive plant and the 2 MWf pilot plant in Chicago.



Figur 7. Bilder på äldre och aktuella anläggningar (Ref. Andritz)

Figure 7. Pictures of old and current plants (Ref. Andritz)

3.2 Skive

3.2.1 Technology

Carbona has supplied a 28 MWf biomass gasification based CHP plant to Skive Fjernvarme in Denmark to produce 5.6 MWe and 11.3 MW of heat. The plant electrical efficiency is 28% (LHV¹) and overall thermal efficiency of 84%. The plant includes three Jenbacher four-stroke, 20 cylinders, turbo-charged gas engines developed for low-calorific gas combustion. The gas can also be combusted in two 10 MW heat boilers when the district heating demand is high.



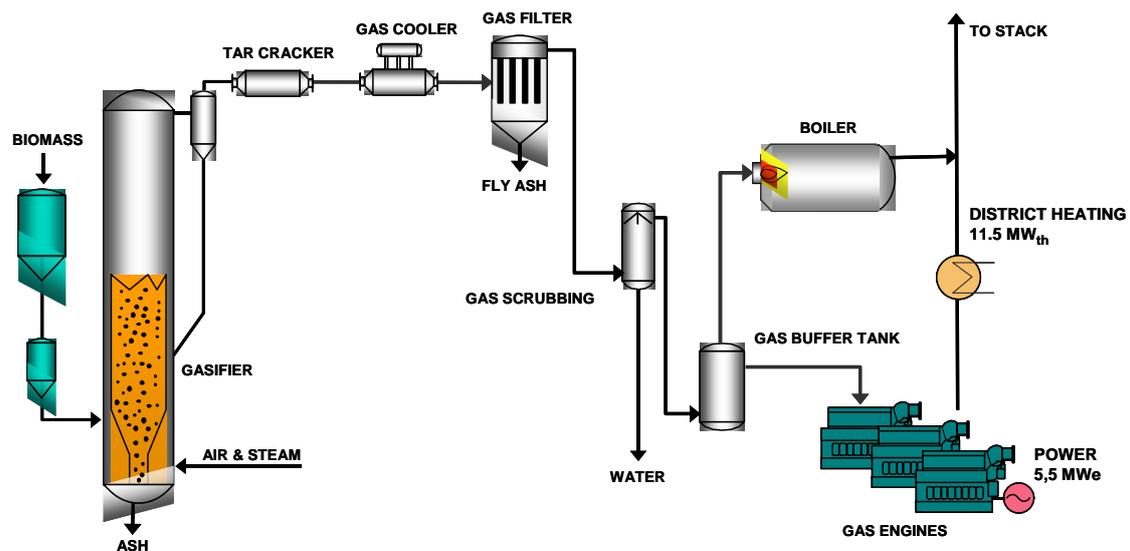
Figur 8. Foto på Skive-anläggningen i mars 2014.

Figure 8. Photo of the Skive plant in March 2014.

The Skive plant can utilize wood pellets (and is designed for chips as fuel with max 20% moisture content but never tried). The feedstock supply is secured with a pellet deal, usually one year, and the Skive plant includes 30-day pellet storage and is owned by Skive Fjernvarme.

The fuel input 19.5 MW (max 28 MW) is fed through a system with two lock hopper into the lower part of the gasifier reactor's fluid-bed. Nitrogen for the lock hopper system is produced at the plant (by VPSA membrane technology from Air Products).

¹ The calorific value of biomass and the produced gas can be defined on Lower Heating Value (LHV) basis or on Higher Heating Value (HHV) basis. The LHV of a fuel excludes the condensation heat of the water in the flue gas after combustion; the HHV includes the heat of condensation.



Figur 9. Schematisk bild på Skive-anläggningen (Ref. Andritz).

Figure 9. Schematic of the Skive plant (Ref. Andritz).

The air-blown gasifier BFB is operated normally at 2 bar (max 4 bar) and 850-870°C and stands 20 m tall. The bed material was earlier dolomite limestone, whereas olivine sand is now used. The consumption is 100-300 kg/day. The load range of the gasifier is 50-130% and the load could be changed by the pressure. The gas velocity remains the same, 1 m/sec for all loads.

The inspection and maintenance of a gasification plant will normally occur once a year during the scheduled maintenance of the overall power plant. The maintenance of the gasification plant requires no special skill or materials since it contains only conventional equipment and material.

The cold start-up of the gasification plant (BFB) requires 14-20 hours depending on fuel, plant size and process configuration. The hot start-up takes a few hours. The gasification plant start-up raises the temperature to 450-500°C and thereon biomass fuel is fed for the gasification process to start.

The turndown ratio of the gasification plant is 50%, limited by the safe fluidization conditions in the gasifier bed. The turndown is determined by the gas usage and can be achieved either with product gas (partial flaring) or with back-up fuel. In emergency situation the gas can be flared off. The flare has been inbuilt and after that it has been no problem with noise from the plant. There are nearby community housing 100-200 m from the plant.

Before the gas can be used as fuel in the engines it must be cleaned and cooled. The first step is tar removal in a catalytic cracker supplied by Haldor Topsøe. The tar reformer is a monolith Ni-based catalyst. It operates at about 900°C and converts the tar to H₂ and CO. About 50% of the catalyst has to be exchanged every year.

In the next step the gas is cooled down to 200°C and passed through a bag filter to remove dust. Then the gas is scrubbed with water to cool it down to 40°C. The scrubber water is filtered (clarification filter) and goes through an activated carbon filter. NaOH is added to balance the pH before it is released into the municipal water system.

If the gas boilers are in operation the gas is fed directly from the bag filter at 200°C. The heat removed from gas cooler, scrubber, engine cooling and exhaust gas is used to generate district heating. The district heating temperature for outgoing produced hot water is 73°C whereas it was earlier 105°C, with a return from the district heating network of 48°C.

3.2.2 Operational experience

The plant was commissioned in Sept 2007. Staged start-up followed, first with gasifier then with reformer and scrubber operation. The start-up of the first engine was in March 2008 with acceptance of the gas quality for the engine model. The installation of the two remaining gas engines started in the summer of 2008. Start-up of the 2nd and 3rd gas engines took place in November 2008. The operation was followed with 2-3 engines through the spring of 2009, with overall plant control adjustment. Full operation has commenced since the end of August 2009 with all three engines. The original reformer catalyst was replaced with Haldor Topsøe catalyst in summer 2009.

The plant is designed for wood chips but currently is running on wood pellets (about 8 mm diameter) as feedstock. The reason for that is that in case of wet wood chip operation the fuel has to be dried below 20% but the Skive plant is not equipped with fuel drier and there is no developed market for dried wood chips as a single fuel in Denmark. It is estimated that the dried wood chip fuel would be only slightly cheaper than pellets (if available). Therefore the plant will continue to operate on pellets except for some testing periods.

The fuel feeding system (following fuel storage, tipping floor, bunker and elevator) is divided in two similar feeding lines based on lock-hoppers. There were no reports on any specific problems related to fuel receiving or handling or feeding. No dusting, no self-ignition, no vapour forming or microbiology degradation. The fuel dust content affects the gasification process negatively; therefore, good quality pellets of low dust content are used.

Fuel feeding screws inject the fuel to the lower section of the gasifier fluidized bed. Feeding screws were adjusted in the early stage of operation to avoid deposit formation related to the pelletized fuel application. The screw conveyor of ash also faced problems (which almost broke the gear). This was solved with fluidization with nitrogen.

Initially dolomite bed material was used in the gasifier to reduce the tar content in the gas. However calcination of the dolomite bed at the gasifier operating pressure and temperature forms calcium oxide which recarbonates in case of process cooling due to interruptions of operation. Recarbonation forms deposition in the cyclone and reformer, which led to clogging problems.

Change of the bed material to olivine diminished this problem. Still deposition develops periodically in the cyclone because of the low density of the fly ash, plugging of the dip leg and in the reformer. Fuel pellets are made of fine wood dust. The disintegrating pellets result in a higher dust carryover than it would be with design wood chips. The dust contributes also to reformer clogging. There is also a possibility of scales from the furnace when there is difference in loads which again leads to plugging. Deposition and dust clean-up takes sometimes up to one week in about every three months of operation.

The reformer is based on monolith type catalyst (surface covered with thin catalyst layer) since the gas borne dust has to pass through the reformer system. The reformer inlet temperature is 920°C by partial burning of the gas; the outlet temperature is 850°C, the heat consumed by the catalytic reformation reactions. The reformer contains monoliths in 9 levels (60 monoliths in 9 baskets). The catalyst itself is nickel based.

At first a monolithic catalyst initially developed by VTT (commercially produced by BASF) was installed. That installation caused both mechanical problems (distortion of the square catalyst baskets due to heating and cooling) and poor conversion of tar. The original ceramic monoliths and catalyst were then replaced in 2009 with metal monoliths and catalyst from Haldor Topsøe. Haldor Topsøe has developed the catalyst formula since that achieving high tar and ammonia reforming since 2011. This solved the problems related to tar condensation in the nozzles and heat exchangers of the scrubber system and naphthalene deposition in the gas engine gas mixer system.

The first generation were squared which made it difficult to fit them together and take them out during maintenance as the temperature made them susceptible for deformation and bending. The new canisters are round which makes it easier to fit together. Above the first bed there is a burner and the temperature is 920°C, dropping to 850°C in lower section. There were deposits on the first bed with carbon and sintered ash. Still there is a problem with gas bypass in the baskets and hot spots. Therefore, there is a plan to redesign the reformer internals applying larger diameter monoliths (60 cm, double the size today) with larger channels to minimize the clogging problem. Today the catalyst lifetime is estimated to about half a year with goal of minimum 1 year.

With the new Ni catalyst (installed in January 2011) the reforming efficiency is good for tar and very high for ammonium which gives no remains in the process water. In addition, there is virtually no nitrogen in white wood pellets as nitrogen is mainly present in the bark of the tree.

Scrubber waste water quality depends fully on reformer performance. The improved performance reduced the hydrocarbon and ammonia content of the waste water significantly. The waste water is discharged through an activated carbon filter directly to the sewage system. There were reports of tar condensation in the gas cooler and in nozzles in the scrubber. The plate-fin heat exchangers were clogged and the solution became to use tube heat exchangers or to circulate the clogged exchangers with soap to clean from tars. There has also been some condensation of tar before the engine where the solution for naphthalene is to raise the temperature but it is not possible to raise the temperature because of the turbo-charged ignition gas engine operation.

The three gas engines (GE Jenbacher) require stable gas pressure which is assured by the gas buffer tank and gas pressure control system which reduces the pressure in the gasifier (2 bar) to the required level (the engine feeding pressure is 150 mbar). After adjustments and some improvements of the gas engines stable and reliable operation was achieved. One disturbance was a fire in the regulator. There is no catalyst in the gas engine flue gas system. The engines meet the required NO_x level and for CO the plant got a permit for higher emissions, however lately it can meet the limits prescribed in the regulations.

The plant is equipped with flare for start-up and shutdown. The flare noise was a problem in early operation due to the nearby residential areas, but it was reduced to 35 dB by applying additional air intake silencers. Despite the improvements the permit prohibits flaring at night, therefore, a start-up procedure is only performed during day-time.

The plant is operated by two operators per shift. The summer stop for service and repair is six weeks long. The plant operation is normally calculated as 262 days per year (calculated as May to June of the next year) and e.g. during the operation year 2012-2013 there were 224 days of operation which gives 85% average availability.

The plant was commissioned in Sept 2007. The accumulated operation hours since summer 2009 are more than 20 000 hours with an average availability of 70-80% with a trend of significant improvements. The recent operation availability is seen in below Table where the number of available days has differed from year to year. In the last operation year the new monolith was installed in five baskets.

Tabell 1. Drifttillgänglighet för olika säsonger vid Skive (Ref. Skive Fjernvärme)

Table 1. Availability for operation seasons at Skive (Ref. Skive Fjernvärme)

Operation season	Availability	Availability excl planned stoppages	Comment
2011-2012	66%	77%	299 available days
2012-2013	76%	85%	285 available days
2013-2014	80%	88%	Until May. New monolith.

After the plant was commissioned late 2007 the availability was very low and not up to design values. The major problems in the early years were mainly these:

1. Poor performing of the reformer.
2. Poor functioning of the fines recycle to the gasifier, frequent cleaning necessary. The problem of fines is not solved completely, yet.
3. Recarbonation by the dolomite limestone bed followed by mechanical blockage (pressure also induces the problem). Other bed materials have solved the problem.

The reason to use dolomite as bed material, initially, was to achieve lower primary tar content. This, however, led to other problems. Another problem is the low life-time of the catalyst in the reformer. There are still some development needs.

Lastly, there have been some problems with the gas engines. The reason is partly due to operating the engines with a fixed output and trying to match the gas production with the gas consumption of the engines. An easier way of operation is to have a varying output with a fluctuating gas production to the engines. This will otherwise lead to imbalances in the gas system and plant control, as the experiences show.

The operating experience conclusion for the commercial demonstration is that high availability could be achieved after major trimming and rebuilding of the catalytic system as well as changing of catalyst. That process took several years and at significant costs. For a new similar plant, the tar reformer availability would be more than 95% with a redesigned tar reformer.

For a new gasification plant, the startup and commissioning period would be 3 months after mechanical completion. The availability of 1st year operation would be about +80% and for normal operation the availability would be +90% with the improved present technology, according to the supplier.

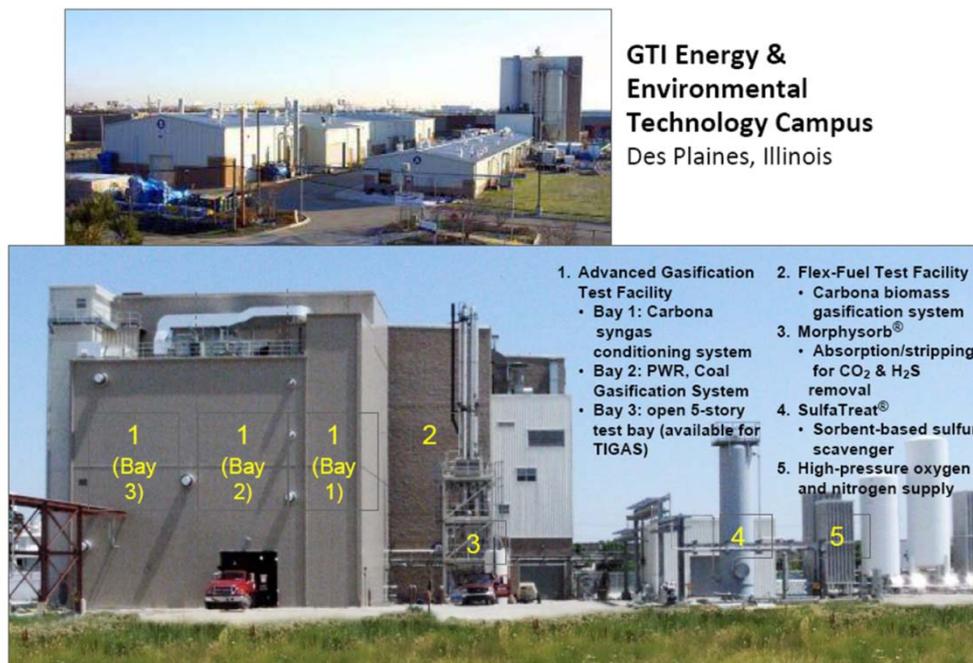
The driving forces to build the gasification plant for heat and power production were:

- Higher efficiency than conventional CHP of Skive size
- Green gas instead of fossil natural gas
- CO₂ reduction
- Green electricity
- Load range and rapid load changes.

The investment cost was €31.5 million. The plant owner got support from EU/USA with 22 million Danish kronor and Danska Energistyrelsen with 12 million Danish kronor. The operation is based on a subsidized feed-in electricity price of 1061 Danish kronor/MWh, which is similar for all gas engine power plants both biogas (based on anaerobic digestion) and thermal gasification. The plant is, however, too small to be truly profitable. For a modern, competitive plant the plant would be larger.

3.3 Chicago

The Advanced Gasification Test Facility (AGTF) at Chicago is located at Gas Technology Institute. The facility is an expansion from the Flex-Fuel Facility which was commissioned in 2004. This facility houses the BFB gasification reactor, whereas the AGTF houses the gas conditioning part. The gasifier is a scale-up and development from an earlier gasification pilot plant, Renugas which has been operated since 1986.



Figur 10. Foto på GTI Chicago-anläggningen (Ref. Andritz).

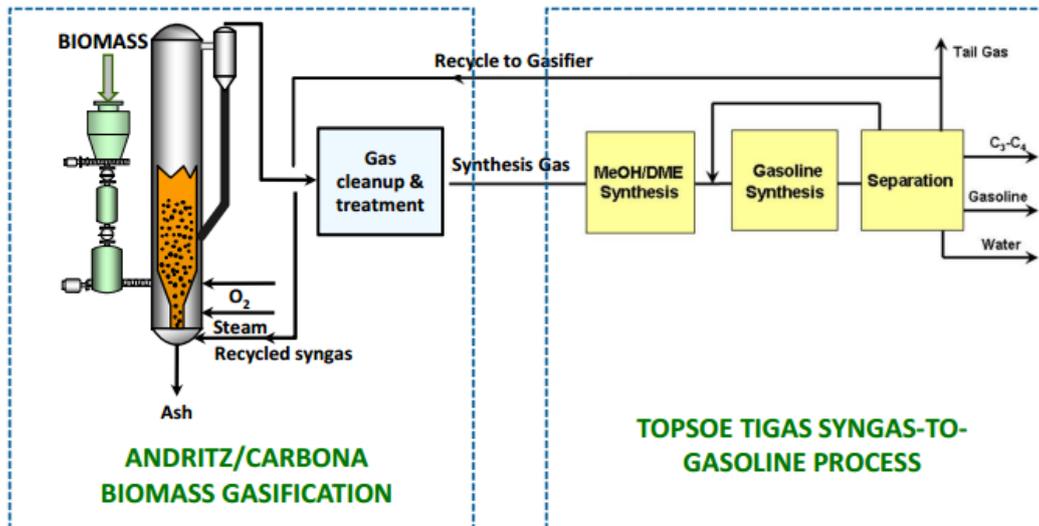
Figure 10. Photo of the GTI Chicago plant (Ref. Andritz).

3.3.1 Technology

The gasification unit is designed to operate at 850°C up to 28 bar and can be used in conjunction with up to 24 tonne per day (TPD) w/air or 40 TPD w/oxygen of biomass. The thermal plant capacity is thus some 4-8 Mwf. The advanced gasification comprises a pressurised, oxygen-blown fluidized-bed gasification reactor with advanced gas cleaning. The gas cleaning consists of a hot gas cyclone, tar and methane and ammonia reformer, gas coolers, gas filter and water scrubber.

The gas is taken to another section which houses the gas processing part. This comprises Morphysorb with absorption/stripping for CO₂ & H₂S removal and SulfaTreat with sorbent-based sulphur scavenger. The product is a cleaned pressurised syngas. The last plant extension project at GTI has been to convert woody biomass into bio-derived gasoline by fully integrating and optimizing biomass gasification and syngas cleanup steps with a process to turn syngas into gasoline. This process (TIGAS) was supplied by Haldor Topsøe and converts methanol to gasoline.

The plant investment cost was \$35 million, with \$25 million support by the US Department of Energy (DOE) integrated biorefineries program (DOE Recovery Act: Demonstration of integrated biorefinery operations). The project objectives are plant feed of 21 tonnes/day of woody biomass and production of 23 barrels per day of gasoline (=3660 litres per day). The construction was completed and the scheduled start-up was for Aug 2012.



Figur 11. "Green Gasoline project" med TIGAS-processen integrerad med förgasningsanläggningen vid Fuel-flex facility vid GTI, Chicago (Ref Andritz).

Figure 11. The Green Gasoline project with the TIGAS process integrated with the gasification plant at the Fuel-flex facility at GTI, Chicago (Ref Andritz).

The project team includes the following partners:

- Andritz/Carbona, a supplier of biomass gasification and gas cleanup plants provided the fluidized-bed gasification plant, a tar reforming unit, and commercialization of the process.
- Haldor Topsøe, a leading worldwide supplier of catalysts and catalytic technology for fuel conversion and upgrading provided the TIGAS process, syngas ultra-cleanup and conversion, and overall project management.
- GTI is the owner/operator of the pilot plant test facility and provided design, construction, and operation of pilot plant plus modeling, data analysis, commercialization support.
- UPM-Kymmene is one of the world's largest pulp and paper companies with more than 100 production facilities. UPM provided collection, handling and transporting of wood.
- Conoco Phillips is a leading oil refiner & contributor to TIGAS. They provided liquids fuels handling, transportation and marketing, sample characterization, pilot plant design, construction, operation and scale-up assistance.



Figur 12. Fuel-flex facility (Ref Andritz).

Figure 12. Fuel-flex facility (Ref Andritz).

TIGAS, an improved version of the methanol-to-gasoline process, converts synthesis gas into gasoline in a single-loop process, thus eliminating the requirement for upstream methanol production and intermediate storage. The resulting gasoline has a Research Octane Number (RON) greater than 93, no sulphur, no oxygen, and contains olefins ranging from 5-15 vol% and aromatics ranging from 30-35 vol%.

3.3.2 Operational experience

The operational experience for the pressurised BFB pilot gasifier has been said to be overall good, but with a weak start. The fuel feed is simple with wood pellets generating a stable gas with constant gas composition and heating value. The tar content was said to be low and the filtration performance good.

The tar reformer in Skive which is based on same Haldor Topsøe technology has been tested +7500 hours with reformer pressure drop stable, temperature control accurate and with no soot formation. The reformer performance is under optimization but no heavy tar has been found after the reformer.

The catalytic tar reformer reforms tars and lighter hydrocarbons, with a controlled reforming of methane. Ammonia is also reduced. The performance of the catalyst has been tested at Chicago as well in Skive in two concepts: “dirty reformer” with dust-containing gas and “clean reformer” for filtered gas. The results have been very good and are seen in below Table.

Tabell 2. Katalytisk tjärreforming med effektgrad (tjärmätning med ETP-metod) (Ref. Andritz and GTI).

Table 2. Catalytic tar reformer performance with reforming efficiency (Tar measurement by ETP Method) (Ref. Andritz and GTI).

Component	Efficiency
Benzene	96%
Toluene	100%
Ethyl benzene	100%
Phenol	100%
Napthalene	98%
Higher molecular weight compounds	95%

Regarding other information on tar reforming there are much information published (e.g. by VTT) which shows +95% tar and methane reforming and +70% ammonia destruction. However catalyst suppliers do not reveal specific information on operational data and catalyst lifetime. In general the anticipated lifetime for similar processes is 1 to 5 years depending on operation and scales.

The pilot plant has been operated in on-going campaigns for gasification at the same time as with completion and construction of the gas cleaning unit and liquid fuel synthesis unit for full demonstration of the complete plant technology. The plant was operating in campaigns from 2009 and reached some 800 total equivalent operating hours until 2010. This was limited by the gas cleaning equipment, whereas the gasification unit has been operated longer.

The plant feedstock is pelletized mixed wood waste – the composition is based on UPM's Blandin Forestry Mill commercial case:

- 25% purchased mill residue (Rapids Energy Center)
- 26% in-woods chips, logging residue
- 49% non-merchantable round wood.

The pilot plant operating experience has over the years covered:

- Pellets, wood chips, bark, logging residue and stump fuel and their mixtures
- Testing of different operation conditions for related equipment and sub-processes
- Testing of different reformer setups and catalysts
- Several test campaigns and long duration testing ongoing.

There is no detailed information published of process data or performance parameters. However, the operating experience has been said to have included an initial shake-down period followed with good operating results and gas quality. The reliability, stability and process performance are well underway to be established.

In October 2013 the team produced about 4000 gallons (15 400 litres) of gasoline suitable for use as a gasoline blendstock. This was used for single-engine emissions testing, demonstrating that renewable gasoline would meet EPA standards in blends up to 80%. The final test campaign in March 2014 produced sufficient quantities for testing to prove that the gasoline can be used in existing automobile engines. Around 7770 gallons have been sent to a blending facility in Michigan to prepare it for a fleet test at the Transportation Research Center in East Liberty, Ohio.

Four pairs of vehicles will each log 75 000 miles comparing performance of the bio-based gasoline blend with conventional gasoline. These results will be available in September 2014 (Ref. Green Car Congress).

The critical process areas for further development of a gasification plant are foremost the reformer and gas filter and gas coolers, which is also where much research activities are placed today. Much experience has been learned from the 30 MWf Skive plant delivered by Andritz Carbona with a similar gasification process, but atmospheric and with air as oxygen medium. Therefore, critical process areas were tested in the development program for functionality to achieve stable operation with set durability, reliability, availability and maintainability (DRAM).

The main bottleneck is and has been fuel feeding and the de-bottlenecking is to have three feeders and to have design philosophy of extending plant capacity of several process trains, e.g. 2x60% or 3x40% capacity. As the other processes are commercially available there are much experience known to achieve the required DRAM.

There are many areas of potential improvement for the future with promising optimization schemes, which of course have also challenges. These can not only be found in the gasification plant but in all process areas. The gasification plant can e.g. be improved with absorption of sulphur already in the fluidized-bed, lower methane gas content and higher operating pressure which all gives better gas quality for synthesis applications. There are also improvements in fuel preparation where torrefaction is a promising technology to increase fuel quality and properties for gasification.

For the other processes the following are in development for commercial use. The ASU can be improved with oxygen membrane separation, and development of Ion Transport Membrane (ITM) technology. The gas cleaning and conditioning process can also be improved with separation membranes and foremost new processes that operate at high temperature. The methanol process can be improved with zeolith membranes, more stable catalysts, also more resilient to sulphur and with higher yields per pass (higher conversion rates).

These are some examples of technology advances to enhance the biorefinery concept and there of course much cost improvements to be made in turn on existing and future process technologies. All in all, the concept is ready for a mature step of first commercialization and for further improvements and optimizations making it truly commercial.

4 Babcock & Wilcox Vølund

4.1 Background

Babcock & Wilcox Vølund is headquartered in Esbjerg, Denmark, with a branch office in the Copenhagen region. Since 2000 the company have been owned 100% by Babcock & Wilcox Power Generation Group, Inc. in Ohio, USA.

Babcock & Wilcox Vølund supplies products within the thermal energy field with their own technologies and the company have about 400 employees. The gasification technology was first developed in Vølund that later was incorporated in Babcock & Wilcox Vølund (BWV). Vølund have sold three units in Japan on licenses to Daio Paper Corporation, Shikokuchuo-shi (latest) and Yamagata Green Power Plant and the Ishikawa Green Power Plant.

4.2 Harboøre

The visited plant is owned and operated by Vølund with a long term contract to sell district heating to a 685 customers and local municipal buildings of the town Harboøre. They have a feed-in tariff for electricity. The power price is 1060 Danish kroner/MWh and indexed versus natural gas prices.



Figur 13. Foto av Vølunds förgasningsanläggning (Ref. Vølund).

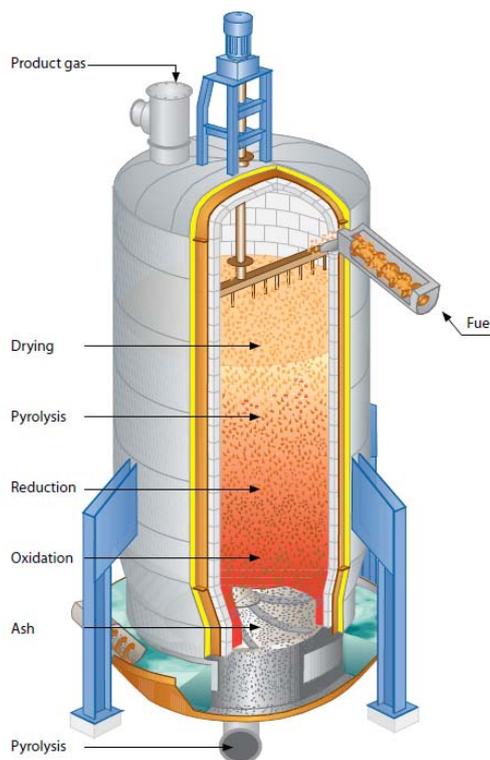
Figure 13. Photo of the Vølund gasification plant (Ref. Vølund).

4.2.1 Technology

Vølund started very early 1988 to develop a fixed-bed gasifier for biomass. In an updraft gasifier the exit gas has a very low temperature e.g. 75°C. The fuel is feed from the top and the level smoothed to have steady pressure drop across the reactor. Early tests with straw showed that too little char was formed to create a stable bed; almost all straw was flash-pyrolysed to gas and tar. After that the development focused on wood.

In the gasifier drying, pyrolysis, char gasification and combustion take place stage-wise. The gasifier is designed as a vertical, cylindrical furnace with internal ceramic insulation and a specially designed revolving grate at the bottom through which moistened combustion air is supplied and participates in the chemical reaction. The wood chips are fed continuously from one side at the top of the gasifier. A levelling device is installed here to keep the surface of the fuel smooth. Furthermore, the levelling device acts as a mechanical level control which controls the fuel supply.

Up through the gasifier a thermal conversion of the biomass into a combustible mixed gas takes place. At the top the moisture in the biomass is evaporated by means of the hot upward gas flow. Further down a pyrolysis takes place, releasing volatiles and tar (150-800°C). Pyrolysis is the heating of organic material without addition of oxidizing gases (air, oxygen, steam). The development of the pyrolysis and the process conditions are decisive for the formation of chemical combinations. The wood chips, which have now turned into charcoal (coke), sink into the reactor, and a reduction (gasification 800-1100°C) with the gasification agents (vapour and carbon dioxide) takes place.



Figur 14. Schematisk bild på Vølunds updraft-förgasare (Ref. Vølund).

Figure 14. Schematic of the Vølund updraft gasifier (Ref. Vølund).

Subsequently the oxidation – the actual combustion takes place (1100-1300°C) with the rest of the charcoal which is burnt into carbon dioxide. The combustion takes place under development of heat. This heat is used further up the reactor. The gas composition depends, among other things, on temperature, pressure, heating rate and residence time in the different zones. The burnt-out wood ash is fed out through a water-lock.



Figur 16. Foto av Vølunds förgasningsanläggning i mars 2014.

Figure 16. Photo of the Vølund gasification plant in March 2014.

4.2.2 Operational experience

After several years of development work the first gasification plant was put into commercial operation in 1993. The plant was started as a district heating plant with first start-up of the gasifier. However, there was a long optimization process and not until 1996 the gasification was considered commercial with steady operation.

However, the plant got CHP capability first in 2000. It took three years of labour to get a product gas with suitable quality. In the course of when the district heating plant was converted into CHP and was taken into commercial operation the following main components were installed:

- Electrostatic precipitator with the tar aerosols removed in the electro-filter
- Two motors with generators, 648 and 761 kWe
- 1000 m³ heat accumulator tank
- Tar and water cleaning system (TarWatC).

However, another system for cleaning the tar-contaminated water from the gas cleaning system – based on ultra-filtration and reverse osmosis – was first tested. This failed to perform shortly after start-up. Therefore, a new technology had to be developed. In the spring of 2002 – after prolonged pilot scale tests (50-60 kg/h of tar-water) – a full-scale system (1200 kg/h) was set in operation and by mid-June 2002 operated satisfactorily and was chosen. A water treatment plant for cleaning the surplus water before discharge into the municipal sewers has been installed.

The primary fuel is wood chips, but successful tests have been made at the plant with other types of fuel, e.g. chunk-wood, bark and waste wood. Using wet, undried wood fuel there has been no dusting and no reports of self-ignition or any special microbiology degradation. The vapour formation and gases are similar to those from wet wood fuels.

The gasifier is operated at atmospheric pressure and has not been reported for bed agglomeration or hot spots. No special fouling or blocking in heat exchangers or corrosion problems. There is very little carbon in the bottom ash. The gas production has not been reported for special fluctuation.

The main problems in the beginning were tar problems and the cleaning of the wash-water. A solution with heated pipes led to coking of the tar. Lowering the top of the gasifier to below 100°C gave a tar that not fouled. The condensed tar is pumpable and possible to recycle or externally burn. The low exit temperature is maintained by moist fuels and adding of steam to the gasifier. In that the fresh biomass acts as a filter for the tar and only a part of the tar reaches the exit. During 2007 to 2008 there was rebuilding of the tarwater for power production.

The engines are turbo-charged with intercoolers to 40°C with water in the cylinder. There has been two backfires in the engines. Maintenance was performed after 10 000 hours by Jenbacher with change of spark-ignition plugs. Currently, spark plug adjustment is performed every 1000 hours and they will last for up to 40 000 hours. After 20 000 hours there is larger maintenance performed and after 60 000 hours a total overhaul with all maintenance performed at site.

The capacity of one engine was increased to 761 kWe through increased turbocharger pressure. Their experience shows with the investment and changes that the gas is easily cleaned of particles and tar for use in a motor. The motor operation at the plant has proven very satisfactory. With over 65 000 hours of experience with the operation of the motor plant the performance targets have been met. The plant managers reported that combustion leaves the motors even less fouled than with natural gas. However, there has been chlorine accumulation in the engines' oil. Therefore the change of oil takes place every 1000 h.

The plant is operated with one engine during summer and two engines during winter. The gas engine is turbo-charged and with spark-ignition. The emissions are low in CO thanks to a catalyst and well below regulation. The test-catalyst has as of today been removed, but the CO emissions are still below regulations.

The plant is fully automatic and operated 24 hours a day with two operators per day. During afternoon until morning it is automatically operated by a computer. The plant produces more than 95% of the district heating requirement of the town of Harboøre.

In summary, there was very poor availability during the first years and before rebuilding in 2001. Not until year 2000 the plant reached readiness for continuous operation. Today, the total accumulated operating hours are about 150 000 for the gasifier and 65 000 per engine.

For a new plant, the startup and commissioning period would be six months. The availability would be >95% (one to two weeks of maintenance) with the improved present technology, according to the supplier.

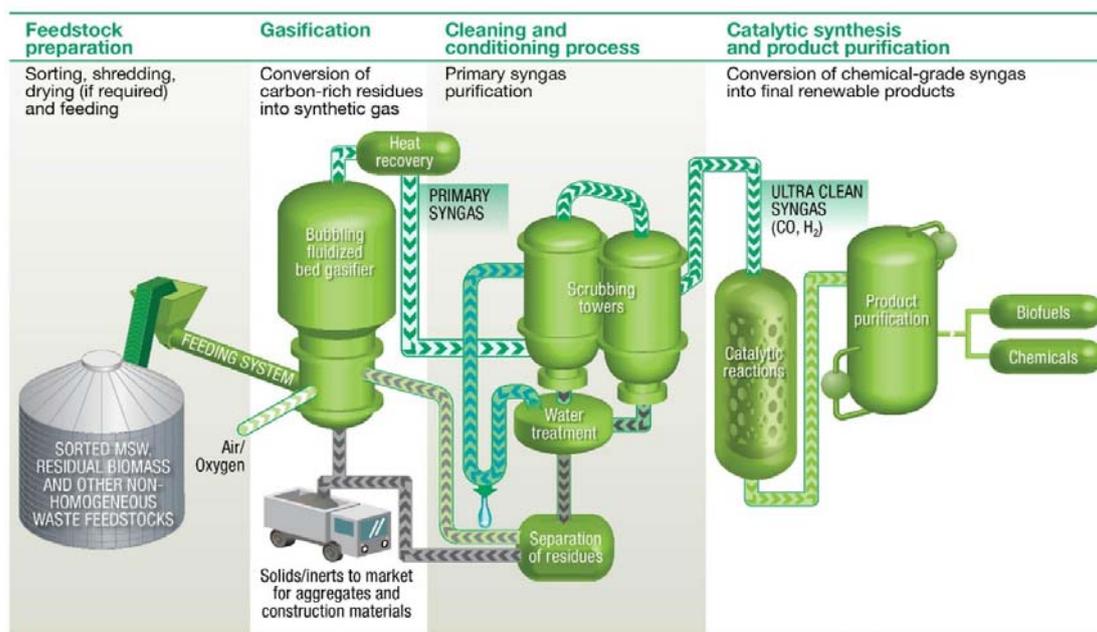
Conclusion: The initial experience was very poor and even after rebuilding it took several years to reach the goal for unmanned operation. Today the availability is remarkably good and the technology have to be considered technically mature.

5 Enerkem

5.1 Background

The initial company was Enerkem Technology Inc. founded in 1999. In 2006, it was restructured as Enerkem Inc. a private entrepreneurial company, having as shareholders a mix of institutional clean-technology venture capital investors, industrial strategic investors and management. Enerkem is headquartered in Montreal, Canada, and have over 170 employees in Canada and the United States. Enerkem develops renewable biofuels and chemicals from waste through the combination of a unique thermo-chemical technology platform for advanced biorefineries.

Enerkem has validated its current, proprietary technology over a period of 10 years using solid waste and other types of feedstock. The company has targeted to process primarily municipal solid waste into syngas, which is sequentially converted into methanol and then into ethanol. The technology is based on a BFB gasifier reactor technology, shown in the Figure below. A total of 25 different fuels have been tested.



* Municipal solid waste

Figur 18. Schematiskt över processen som demonstreras i Westbury (Ref. Enerkem).

Figure 18. Schematic of the process as demonstrated in Westbury (Ref. Enerkem).

The technology has a very long history, starting with the first oil crisis in the 1970s. The first atmospheric fluidized-bed gasifier at a commercial scale was built by Omnifuel, a Canadian company. The gasifier was in operation a few years but with significant problems, e.g. explosions in the flare. Omnifuel went further in the early 1980s to an air-blown, pressurized demonstration plant in the early 1980s in French Guyana supplied to EDF to feed an existing stationary diesel engine. The commissioning was not successful partly due the engineering mistakes.

A demonstration plant was erected in Canada for oxygen-pressurised fluidised-bed gasification. The plan was to run the 20 MWf pressurized gasifier with oxygen and then move to high temperature filter and catalytic reforming for syngas production. The demonstration plant was owned by Biosyn, a state-owned company. Only the first phase was run before the interest for methanol ceased because of lower oil prices in the mid-80s. The gasifier was moved to Sherbrook University. With air and low pressure the capacity was like a pilot plant. Under the leadership of Esteban Chornet it was operated for a long time as an experimental unit. That led to the formation of Enerkem by Prof. Chornet and his sons.

The current development for the gasification-based process technology is to convert sorted municipal solid waste (MSW) and residues from the forest and agricultural industries into transportation fuels, high-value chemicals and electricity. Enerkem refers to their process as carbon recycling as it chemically recycles carbon that would otherwise be trapped in landfill waste. The process is complimentary to traditional recycling practices as value is generated by converting the carbon in traditionally nonrecyclable waste to renewable energy sources.

5.2 Westbury

Enerkem operates two plants in Québec, Canada: a pilot plant in Sherbrooke started in 2003 and a commercial demonstration facility in Westbury started in 2009 as shown in the Figure below.

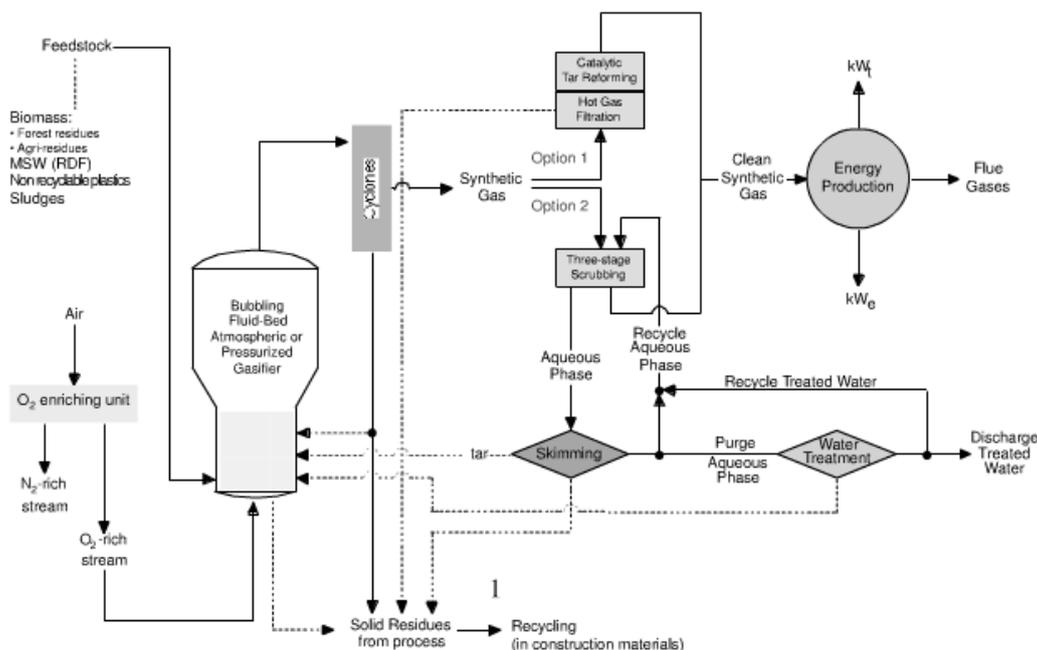


Figur 19. Bild på Westbury-anläggningen med transportörer av bränsle till ingången av matningssystemet. Processerna för förgasning och metanolsyntes är placerade inuti byggnaden (Ref. Enerkem).

Figure 19. Picture of the Westbury facility showing the conveyors transporting the feedstock to the entrance to the gasifier feeding system. The gasification and methanol synthesis units are located inside the building (Ref. Enerkem).

5.2.1 Technology

The process combines gasification and catalytic synthesis and in between gas conditioning steps to generate a tailored syngas product suitable for conversion to premium products, see Figure below.



Figur 20. Schematiskt på Enerkem med förgasning och gasreforming och reningsprocesser (Ref. Enerkem).

Figure 20. Schematic of the Enerkem gasification and gas reforming and cleaning process (Ref. Enerkem).

The raw feedstock is pre-treated thereby dried, sorted, and shredded. The feedstock (fluffy RDF or shredded wood) is introduced into an appropriately designed silo system from where the material is transferred to the gasifier's feeding system. The latter, an innovative design, is capable of

- (i) Handling fluffy materials, shredded wood and straw as well as pellets and
- (ii) Changing the type of feed.

An important characteristic of Enerkem's technology is that the gasifier feeding system is capable of handling fluffy material with no need for pelletizing. Enerkem specifies moisture of 20 wt.% for introduction into the gasifier. Such level can be conveniently achieved using low grade heat or, in many cases, by simple air convection in a conveniently designed storage area. The feedstock is introduced into the gasifier's fluid bed (operated in a bubbling regime with two seconds residence time), where it is converted into a primary syngas and (vapour) intermediates as well as char. The auto-thermal gasification is accomplished using oxygen-enriched air or oxygen together with steam and recycled carbon dioxide. The fluidizing gases are introduced through nozzles.

The relatively low operating severity of the gasifier fluid bed, at temperatures in the 600-700°C range and a pressure range comprised between 2-10 bar (abs), is a characteristic of Enerkem's fluid bed operation.

The upper part of the gasifier vessel, i.e. the free board, is used as a thermal cracker and reformer. An added external reformer is an alternative and is used in the AERF Pilot plant. To accomplish effectively the thermal cracking and reforming, the gas produced at the fluid bed, in its upward movement, is progressively heated by injecting, at appropriate velocities, oxygen-containing streams.

The temperature in the upper free board reaches the levels at which steam- and carbon dioxide-driven thermal reforming is kinetically possible. The entrained char particles also convert part of their carbon into gaseous species during the reaction time allowed by the design, to effectively.

Computational fluid-dynamic and kinetic modelling is used (coupled) to optimize nozzle configurations and operational parameters. The benefit of this approach is a good control of:

- a) The carbon conversion to reduced carbon-species in the syngas,
- b) The unconverted carbon and
- c) The tar formation.

The syngas from the gasifier is conditioned for downstream use by sequential cleaning using a combination of established techniques in the petrochemical sector (three-stage scrubbers). The larger particles present in the heterogeneous feeds stay in the bed and are withdrawn from the bed together with alumina sand, using a proprietary design that cools the solids, depressurizes and sieves them, recovering the alumina-rich fraction which is re-introduced into the gasifier. The fraction containing the inert particles is a residue that can be used as aggregate in direct applications, such as road construction. Since the process is a net producer of water given the moisture present in the feedstock, water is purged and needs treatment (not different than petrochemical plants wastewater) before reuse.

From the water scrubbing sub-system, a sludge containing the fine char particles is recovered. It is essentially free of tar since the latter, together with the mono-aromatics, is absorbed in the last scrubber of the cleaning sequence using an organic solvent. The aromatics are recovered and become co-products of the process. The tar-free char, which contains some carbon, has a variety of applications.

The cleaned syngas from the above steps is then compressed to a Medium Pressure (MP) level and subjected to an Acid Gas Removal step. CO₂ is absorbed along with H₂S and minor amounts of impurities. The unit is a physical wash with methanol as absorbing medium like the Rectisol process. The syngas, after this step, is essentially comprised of H₂ and CO and CH₄, a few vol.-% of CO₂, and traces of impurities. Such gas is further compressed to High Pressure level (<60 bar) prior to flowing through a guard-beds system that brings the impurities (tar, metals, chlorine, sulphur and carbonyls) to levels that result in long time-on-stream for the methanol catalyst.

Enerkem uses a three phase reactor of its own design for the methanol synthesis, similar to Air Products' Liquid-Phase Methanol slurry-based technology. The CH₄ present in the syngas acts as an inert in the synthesis and exits the methanol reactor as a component of the tail-gas. Following membrane separations, the recovered CH₄-rich stream is used to generate H₂ and CO via a catalytic steam reformer. The H₂ and CO thus produced are added to the ultraclean syngas to adjust the desired H₂/CO-ratios entering the methanol reactor.

Methanol is the key platform intermediary produced by Enerkem. It is put in the market directly or used, for building C-C bonds. In its Pilot plant in Westbury, Enerkem uses the methanol, together with CO and H₂ recovered from the tail-gas, to produce ethanol in a two-step catalytic gas phase process. The methanol forms methyl acetate and with hydrogenolysis and added hydrogen into ethanol.

The data base obtained in the Pilot plant has been used as basis for the design of the commercial process to be added to the Edmonton EAB plant in 2015. Obviously, once the ultraclean syngas is available it can be used for other catalytic syntheses, using thermo- or bio-catalysts. The commercialization development has focused on sorted urban waste as main (low-cost) feedstock with a short-term commercial market. The feeding system using diversified fluffy low density material, as well as higher density materials, is clearly distinct from existing feeding systems.

The gasifier fluidized-bed technology is based on existing petrochemical knowledge and is geared to avoid high temperatures that result in undesirable softening/melts leading to agglomerations. Under such conditions the fluidized-bed operates as a quasi-pyrolyzer under partially oxidizing atmosphere. Leaving the fluidized-bed the mix of permanent gases, intermediate vapours and entrained fines is heated by injection, through appropriately designed nozzles, of oxygen-containing streams. Cracking/reforming takes place in the overall steam/CO₂-rich atmosphere.

In its commercialization efforts, Enerkem uses a modular concept by means of which onsite construction is limited to interlinking the constitutive sub-modules. The latter are fabricated in specialized machine shops and transported to the project plant site where the sub-modules are interconnected and linked with the integrated distributed control system. The process engineering package is developed by Enerkem. In Edmonton, the procurement and plant construction have also been managed by Enerkem, the owner of the plant.

5.2.2 Operational experience

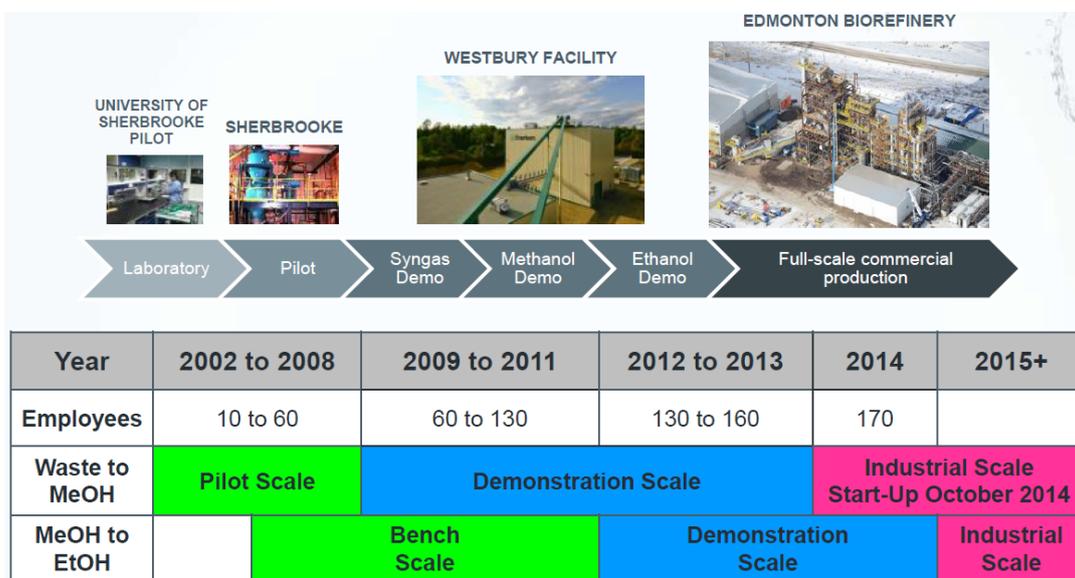
Enerkem operates two plants in Québec, Canada: a pilot plant in Sherbrooke started in 2003 and a commercial demonstration facility in Westbury.

Sherbrooke pilot plant (150 kg/h as nominal feed input) started in 2003. It followed the work initiated at the University of Sherbrooke where a unit with 50 kg/hour feed input capacity operated in research campaigns for +2000 hours, proving the basic concepts.

The Enerkem pilot plant followed in 2003, already outside the premises of the University. It processed up to 200 kg/hour of 25 different fuels for +4000 hours of accumulated operation. A 20 kWe gas engine was also installed and operated with a slip-stream of the syngas when needed. A methanol synthesis reactor using 1 kg of catalyst was also installed using, as well, a slip-stream of the syngas. The initial data on the methanol synthesis was obtained in this reactor.

Westbury demonstration facility (1.5 t/h as feed input). The plant operations started in 2009 with the production of conditioned syngas from treated wood (spent electricity poles and railroad ties as a feedstock). Production of biomethanol at the facility started in 2011. The facility has run +5000 hours until the autumn of 2014. The Methanol-to-Ethanol Pilot Plant (maximum capacity is 40 000 litres/year) was added in 2012 and has been operated in campaigns since. It is an integrated facility with recycle loops and separation unit operations around the two reactors that carbonylate the methanol and hydrogenolyze the intermediate produced. The end product is the water in ethanol azeotrope obtained after the final integrated distillation tower. The plant can be operated by three operators with 24-shift.

The successful pilot and demonstration experiences are now the basis for the design into commercial scale. Enerkem had a total of +9000 hours logged of operational time between 2003 and 2013 in its pilot and demonstration facilities. The scale up factor was <10 and it has been kept at <10 from Demo to Commercial in Edmonton (described below). Such prudent approach in scaling up led to a rather successful commissioning at Westbury, despite that the process consists of a long series of steps. It is also proceeding well in Edmonton where syngas and methanol production are expected to take place in the autumn of 2014.



Figur 21. Illustration of den rigorösa vägen till kommersialisering med företagstillväxt och sekventiell teknikutveckling med anläggningar (Ref. Enerkem).

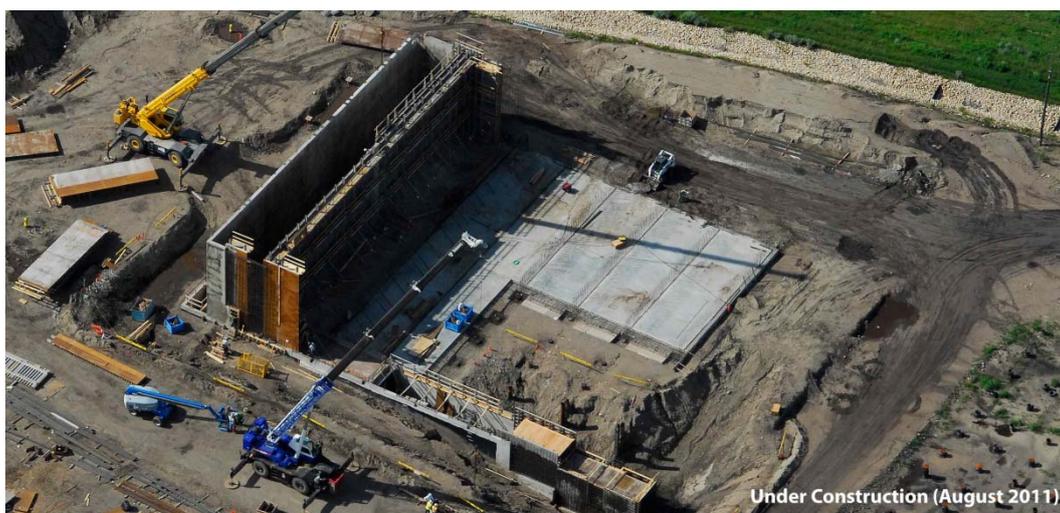
Figure 21. Illustration of the rigorous path to commercialization with company growth and the sequential technology development with plants (Ref. Enerkem).

5.3 Edmonton

The first commercial unit is located in Edmonton and is owned by Enerkem's subsidiary, Enerkem Alberta Biofuels (or EAB). The plant is now (Oct. 2014) in its commissioning phase. The scale up factor is 7.25 (2 t/h dried fuel as maximum capacity routinely converted in Westbury and 14.5 t/h as the design capacity in Edmonton). The gasifier reactor is 60 feet high (ca 18 metres). The gasifier operated a few days in June and the goal is 10 days of continuous operation. One problem encountered was thermal expansion of the gasifier vessel. The downtime cause so far has been in rotary equipment.

The 25-year agreement between the City of Edmonton Waste Management Center (EWMC) and Enerkem, involves the transfer of 100 000 tonnes RDF/year dry basis prepared at the existing Integrated Processing and Transfer Facility of the EWMC.

The project was granted an environmental permit and construction started during summer 2010. The startup was originally scheduled to 2012. However, the plant was officially opened in June 2014, after its mechanical completion. Since then, the plant is under commissioning mode. Syngas and methanol production are expected to begin during the autumn of 2014. The methanol-to-ethanol island is to be erected in 2015 and commissioned in 2015-2016.



Figur 22. Bild över byggplatsen vid Edmonton (Ref. Enerkem).

Figure 22. Picture of the Edmonton construction site (Ref. Enerkem).



Figur 23. Bild över byggplatsen vid Edmonton (Ref. Enerkem).

Figure 23. Picture of the Edmonton construction site (Ref. Enerkem).

5.3.1 Technology

Enerkem have a good technical background for the commercial plant through the operation of the pilot and demonstration plants. Basically the plants have been scaled up with same technology concept and design basis.

Besides the EAB plant, Enerkem partnering with the City of Edmonton's Waste Management Center of Excellence (EWMCE), has installed and teams with the EWMCE to operate, in the Advanced Energy Research Facility (AERF), a 300 kg/h gasifier coupled with a methanol synthesis reactor.

Such pilot plant has operated, in campaigns, since the summer 2014. It is adjacent to the pilot sorting and recovery facility (owned by the EWMCE) where diversified feedstocks can be appropriately prepared, as well as blended (if desired), and sent, via pneumatic transport, to the pilot plant for conversion.

The EAB plant and the AERF Pilot plant efforts have been supported by the Alberta Government through two agencies (Alberta Innovates Energy and Environment Solutions, AIEES; and the Climate Change and Emissions Management Corporation, CCEMC).

5.3.2 Operational experience

Enerkem's first full-scale commercial facility is currently in commissioning and a similar project is under development in Pontotoc, Mississippi. Both these plants will produce methanol and cellulosic ethanol.

According to the supplier, the startup and commissioning period for a new Gasification plant would be 2 months after mechanical completion. The availability of 1st year operation would be about 81% and for normal operation the availability would be 91% with the improved present technology.

Similarly, for a new Gasification + Methanol plant, the startup and commissioning period would be 3 months after mechanical completion. The availability of 1st year operation would be about 73% and for normal operation the availability would be 91% with the improved present technology.



Figur 24. Vy över Edmontons Enerkem Alberta Biofuels anläggning vid invigningen 4 juni 2014 (Ref. Enerkem).

Figure 24. View of the Edmonton's Enerkem Alberta Biofuels plant at its inauguration date: June 4, 2014 (Ref. Enerkem).

5.3.3 Forthcoming plants

Pontotoc

The sister plant to Edmonton is developed in Pontotoc, Mississippi, under its wholly-owned U.S. affiliate, Enerkem Corporation. The plant was scheduled for construction in 2009. However, there is still no completion and five years have passed. The planned \$100 million ethanol plant Enerkem Mississippi Biofuels was last said to begin construction in the latter part of 2013.



Figur 25. Konstnärlig bildbeskrivning av anläggningen i Pontotoc (Ref. Enerkem).

Figure 25. Artist interpretation picture of the Pontotoc facility (Ref. Enerkem).

Enerkem signed an agreement with the Three Rivers Solid Waste Management Authority of Mississippi for the supply of 190 000 tonnes of unsorted municipal solid waste per year. A portion of the waste will be recycled and the other portion will be converted into ethanol. Expected capacity is 36 000 m³ of ethanol per year.

The company received a US\$ 50 million award in 2009 from the U.S. Department of Energy. In January of 2011 it was awarded US \$80 million loan guarantee by the U.S. Department of Agriculture. It successfully met the federal environmental assessment requirements.

The last information on this project was that the supply and availability of the raw material was contingent on the financing and construction of a Municipal Recovery Facility for which no agreement has apparently yet been reached.

Varenes

Enerkem has engaged in a joint-venture agreement with the largest first generation ethanol producer in Canada, Ethanol GreenField (EGF) to build a 100 000 tonnes RDF/year plant in Varennes, Quebec, adjacent to the EGF existing distillery.

This new addition will add 38 000 m³ ethanol/year to the current 150 000 m³ 1st generation ethanol/year already being produced. The Enerkem-designed plant is to begin operations in 2017. It will use urban waste known as ICI (Institutional, Commercial and (small) Industry) as feedstock following sorting and recycling.

This project has the support of both the Federal Government of Canada (through its agency, Sustainable Development Technologies Canada) and of the Government of Quebec (through the Ministry of Energy and Natural Resources of Quebec).

6 AMEC Foster Wheeler

6.1 Background

Amec Foster Wheeler plc is a British multinational consultancy, engineering and project management company headquartered in London, United Kingdom. AMEC made an acquisition of Foster Wheeler on 13 November 2014. In the report, the company is referred to as “Foster Wheeler” as the gasification business itself is the same.

Foster Wheeler Power Group Europe is headquartered in Helsinki, Finland with engineering office in Varkaus and part of the well-known Foster Wheeler Corporation, the global engineering and construction contractor and power equipment supplier. The companies are located in Finland, Poland, Spain, Germany, Sweden, Thailand, and Indonesia. Engineering takes places primarily in Varkaus and Madrid, and R&D in Karhula, while manufacturing takes place in Finland, Poland, and Spain.

On a worldwide basis, Foster Wheeler is a recognized leader in the engineering, design, and supply of circulating fluid bed boilers, supercritical and sub-critical pulverized coal units, heat recovery steam generators, industrial steam generators, package boilers, selective catalytic reducers, and general boiler services. The company is a specialist in turnkey power plant projects, advanced boiler technology, and associated maintenance and service and CFB boilers in particular. The company has a reference list of more than 210 CFB units, and has an approximately 50% share of the world market for this type of boiler. The BFB reference number is over 130 plants and there are eight commercial fluidised bed gasifier references.

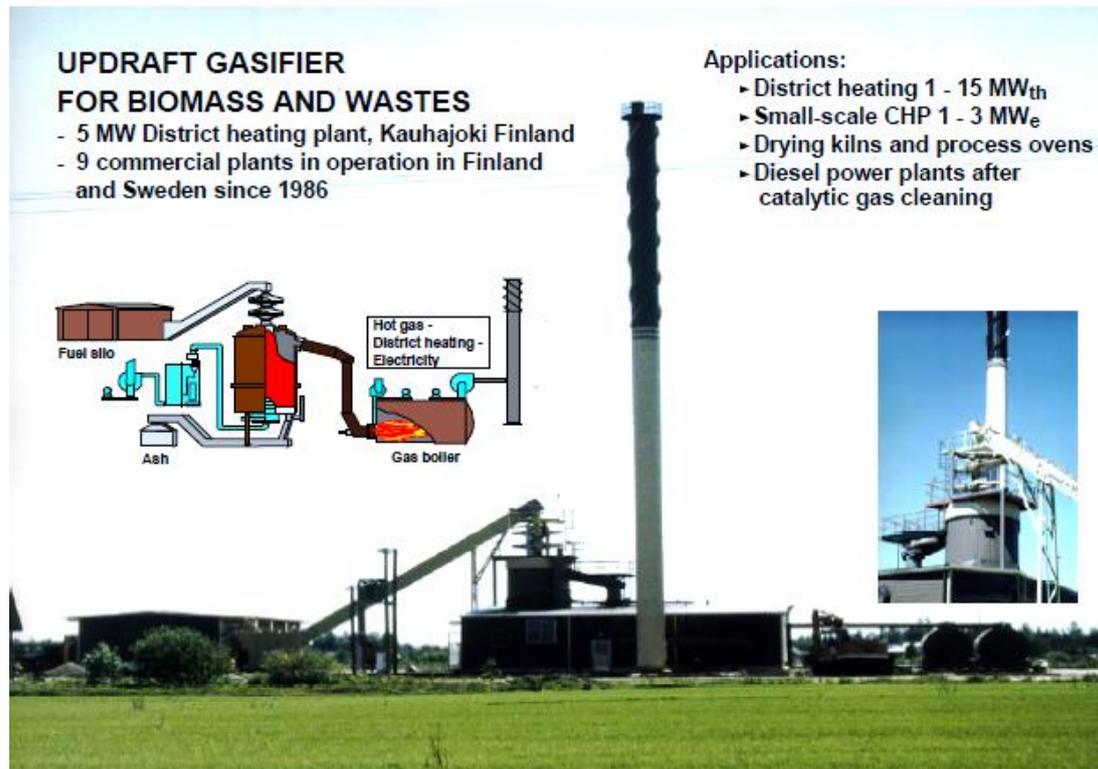
Foster Wheeler owns several gasification patents and gasification technologies, which have been developed during several decades. A number of these were originally developed by Ahlstrom Pyropower (API). Foster Wheeler acquired API and has likewise acquired these gasification technologies including the pressurized circulating fluidised-bed gasifier (Bioflow). The Swedish power company, Sydkraft (now E.ON), constructed in the 1990s the Värnamo IGCC plant to demonstrate the Bioflow technology. Foster Wheeler acquired a subsidiary of Ahlstrom that built the gasifier, and Bioflow became part of Foster Wheeler in 1995. The commercial project development in biomass gasification is currently managed by Foster Wheeler Italia.

The different gasifiers are the atmospheric updraft gasifiers (Bioneer), atmospheric circulating fluidised-bed gasifiers (Pyroflow), and the pressurized circulating fluidised-bed gasifiers (Bioflow). These systems have accumulated large experience with different fuels, including plastics and biofuels.

6.2 Bioneer

The simplest gasifier, the Bioneer atmospheric updraft gasifier was developed for converting biomass to heat for small districts. A total of ten Bioneer gasifiers have been installed (including the first experimental pilot plant). The maximum plant size is 10 MWf with most of the plants in the range of 4-8 MWf.

The fuel requirements are low but fuels with high fractions of fines like crushed bark and sawdust are not suitable. If the feedstock is too fine then it cannot be effective in the process. The fuel should also contain less than 45% moisture for stable gas combustion. These gasifiers are simple to operate, and the technology is well proven.



Figur 26. Bild på en Bioneer-anläggning med schematisk processbild (Ref. Foster Wheeler).

Figure 26. Picture of a Bioneer plant with schematic process (Ref. Foster Wheeler).

6.2.1 Technology

This technology was originally developed by Dr. Ilkka Haavisto in his own company Bioneer. The Bioneer technology was further developed in cooperation with VTT in the first half of the 1980s. A total of eight plants were built during the mid-80s by Bioneer. The Bioneer company was then sold to Ahlström (later Foster Wheeler) and Dr. Ilkka Haavisto was prohibited to build new plants during a period of five years. In 1996, Foster Wheeler built another plant making it number nine and the 10th counting the first pilot plant.

When Ahlström was later sold in different parts to different companies the technology was divided upon several companies e.g. Carbona OY (now Andritz) where all could be a potential supplier. After year 2000 Dr. Ilkka Haavisto developed (again with VTT) a new gasifier and gas cleaning system (called Novel) in his company Condens OY. This technology has now been sold to a not disclosed company.

The Bioneer technology is based upon a rather traditional updraft gasifier. The gasifier is fed with fuel from the top and the fuel passes the different zones: drying, pyrolysis, char gasification and char combustion (as in all updraft gasifier reactors). The special feature with the Bioneer design is that it mechanically is very robust and intended for automatic operation. The gasifier is a refractory-lined cylindrical vessel with a rotating con bottom.

The intended size range is about 4-10 MWf with applications for district heating drying and other furnaces. The gasifier operates with wet biomass and peat fuels without a dryer. The gasification and sintering in the bottom part (temperature) is controlled by adding water to the gasification air. The technology principle leads to a gas with a low exit temperature (100°C) and a lot of tars. A typical gas for 41% moist wood chips has a heating value of 6.2 MJ/Nm³. The tar content is in the 50-100 g/Nm³ range. The gas is piped to a burner developed for this gas. This pipe has to be cleaned from tar after a few weeks (about 2-6 weeks) by adding air in the pipe and burning away the tar deposits online. This has proved to be a large operational problem with fires and explosions.

As an example of the Bioneer technology one gasification plant is here studied further. Near Östersund, in the city of Lit, Byggelit a fibreboard manufacturing company holds two sub-atmospheric updraft gasifiers of 4 MWf and 6 MWf, originally intended for peat but today fed with producer biomass residues, which were built in 1986 with monetary support from Länsstyrelsen.



Figur 27. Foton på Bioneer updraft-förgasaren vid Byggelit i Lit utanför Östersund, Sverige.

Figure 27. Photos of the Bioneer updraft gasifier plant at Byggelit in Lit, Östersund, Sweden.

The gasifier units with separate gas chamber burners and boilers were delivered by CP Energi on a license from Oy Bioneer AB (now Ahlström) and with technology from Kari Salo (now Andritz Carbona OY), who acted as Project Manager. The gasifiers produce hot water of 195°C and 225°C for the fibreboard manufacturing process, specifically for the fibreboard press machines.

The sensible heat in the flue gases is used as drying application of ground wood fibres (which constitutes the raw material for fibreboards), where the moisture content is lowered to 2 wt.% by direct heat exchanging in a rotary drum dryer. The remaining available latent heat is used to warm clean air for direct facility heating by flue gas condensing.

The gasifier comprises a top fuel feeder, a brick-lined steel cylindrical reactor vessel with a rotating grate and an ash discharge system at the bottom of the reactor. Air is fed by a blower at the bottom of the reactor through a fixed bed, where oxygen reacts with part of the fuel carbon and hydrogen in exothermic combustion reactions as to release the necessary heat for endothermic gasification reactions to take place.

The fixed bed in the reactor, which is maintained at 700-900°C to ensure that ash is prevented from sintering and slagging, is monitored with thermocouples that are placed at the inside reactor refractory wall through drilled holes of the reactor. In addition, level detectors alarm if the bed height limits are reached due to either excessive fuel feeding or by bed combustion.

It is desired to control the unburned feedstock layer above the so-called glowing bed in order to avoid through-burning of the bed, which is hazardous. Although ash has been subjected to cause sintering and slagging on the reactor walls the brick-lining is the same since the start of operation in 1986.

The fuel, typically with a moisture content of 50 wt.%, is a mixture of waste pulp wood, sawdust from neighbouring sawmills (furthest distance of transportation is 100 km), wood chips, and ground fibreboard residues. Sander dust from the fibreboard manufacturing process is also used, however, not in the gasifier but fed directly to the gas burner.

The sander dust is too fine in particle diameter size to efficiently burn in a fixed bed, i.e., oxygen is prevented by the dense bed layer to penetrate further inwards, thus a fixed-bed combustion process was deemed unsuitable when the technology process was chosen. However, today's combustion processes, as e.g. marketed by Sermet OY (now incorporated in Wärtsilä), developed from the early updraft gasification research have overcome this problem. Nonetheless, combustion processes normally faces problems such as dust-laden flue gases and unburned hydrocarbons resulting in a lower thermal efficiency.

Although sander dust erodes fan rings, pipes, cyclones and others, the explosion risk was said to be small. As an explosion reaction can only take place when oxygen and fuel is present in the right proportions and a heat source is available (however, could be spark-ignited), the risk is at minimum as long as one of the parameters is missing.

On the other hand, the generated gas, being highly more explosive, must be controlled. Consequently, as a security measurement, a downstream fan places the whole process in sub-atmospheric pressure and thus sucks gas from the gasifier, preventing gases to escape through the fuel feeder or the ash discharge system.

6.2.2 Operational experience

The Bioneer technology was developed in a pilot plant at the Bioneer works in Hämeenlinna, Finland with a capacity of 1.5 MWf. Extensive testing with different fuels took place and also guided the choice of acceptable fuels with reasonable particle sizes and low content of fines.

During the 1980's a total of eight gasifiers were erected in seven different plants. Two plants were built in the northern Sweden in Lit outside Östersund for the dryer to a chip board (MDF) factory and one plant in Vilhelmina for district heating. The other plants were built in Finland, with the first in operation from 1986 and the others shortly thereafter, see Table below for details.

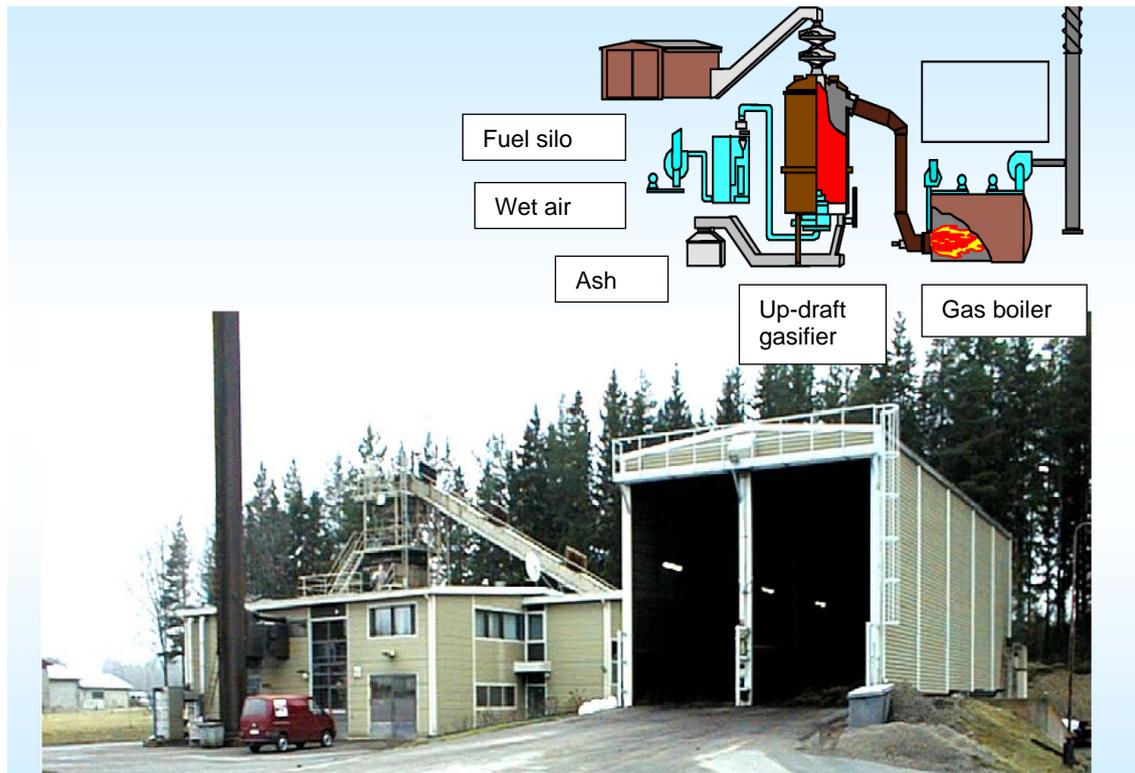
Tabell 3. Lokalisering av "Bioneer"-förgasarna, av vilka alla är stängda. Allihopa levererades av Bioneer förutom Ilomantsin Lämpö-verket som levererades av Foster Wheeler.

Table 3. Location of the "Bioneer" gasifiers, which are all closed now. All were delivered by Bioneer except the Ilomantsin Lämpö plant which was delivered by Foster Wheeler.

Location	Country	Commissioning	Capacity
Jalasjärven Lämpö	Finland	1987	5 MWf
Kauhajoen Lämpöhuolto	Finland	1985	5 MWf
Kiteen Lämpö	Finland	1986	6 MWf
Oulun Seudun Lämpö	Finland	1985	5 MWf
Parkanon Lämpö	Finland	1986	4 MWf
Ilomantsin Lämpö	Finland	1996	6 MWf
Byggelit, Lit	Sweden	1986	4 MWf
Byggelit, Lit	Sweden	1986	6 MWf
Vilhelmina Värmeverk AB	Sweden	1986	5 MWf

One of those plants (Jalasjärvi) had already in 2005 accumulated 145 000 hours of operation, and by now it should be over 200 000 hours in that plant. The total accumulated operating hours for these Bioneer plants would today account for at least 1.5 million hours, which in itself is a historic achievement.

The northern plants in Sweden closed in 2005 due to closing of the board factory but were restarted not long thereafter as the former private owner took control of the factory and reopened business. The southern plant in Vilhelmina closed as a district heating plant. Most of the plants in Finland were however still in operation up to recent years and may possibly be in operation locally.



Figur 28. Värmeverket på 5 MWf vid Jalasjärvi, Finland har varit i drift sedan 1987.

Figure 28. The 5 MWf Bioneer gasification district heating plant at Jalasjärvi, Finland which has been in operation since 1987.

The operating experience of the plants at Byggelit will from here be detailed as examples of the technology. The gasifier units have been in operation since 1986, with several problems the first couple of years due to testing with very low-grade fuels. However, since 1991, when they changed to high-grade fuels, the gasifiers have been operated close to 100% availability and with no forced outages. The feedstock is wood chips but also spill and crushed boards from the board production, and other waste materials have been used, which have been thought suitable and with not too high moisture content.

The single largest problems with these plants are the gas seals and to keep them gas tight at the fuel feeding as the process condenses the product gas. The tar that was condensed on the surfaces was very toxic and very difficult to clean. In addition, the work difficult to make adjustments and repairs with hot work and an explosive gas. One particular difficulty was accidental firing in the gas pipes and pulsating burning in the gas bellows. The two gasifiers at Byggelit have been in operation up until 2013. The smaller gasifier of 4 MWf was used to heat the chip-board press and the factory building. The gas burner bellow was damaged in a fire in April 2013 and the decision was to take it out of operation for good (complete damage). The second gasifier of 6 MWf was used for the main dryer. This was taken out of operation in the summer of 2013. It is still standing but closed down and will be dismantled in the end of 2014.

Overall, the plant availability has been sufficiently good for the production at the plant, according to the supplier. The gasifiers have functioned well but the side-systems have had many issues. On top of that, there were smells, hazardous gas leaks, dangerous gas pipe firing, tripping heat radiation meters. In conclusion, the plants needed a lot of maintenance when there were problems.

The total accumulated operating hours are calculated as in principle non-stop operation until 2013 with 6 weeks maintenance stoppage each year from year 1986, apart from the first couple of years with lower performance. The total number of hours are about 400 000 together. Nevertheless, important lessons learned include:

- High moisture content in the fuel in combination with a high ash content yield glassy slag on the reactor walls,
- Too low reactor bed temperature will result in water in the discharged ash (because of less cooling water evaporated), which in turn produces a soup that penetrates bearings and valves and form a highly viscous concrete-like fluid,
- Tar is deposited on the inside walls of the gas outlet pipe and must be burned away from time to time by feeding oxygen through simply opening a lid (in analogy with "burning out" a car muffler),
- The gas burner must be supported by an oil burner at all times to prevent a flame-out caused by gasification of large chunks of snow and ice (regularly, gas is pulse-combusted in an pumping mode due to moisture variations in the fuel and explosions in the gas combustor have occurred, deforming its walls),
- Natural spherical gravel of pee-size instead of crushed brittle gravel must be used as bed material, (only when starting up the gasifier) to prevent the rotating grate from over-heating; because of the crushed gravel's poor attrition properties; the crushed gravel breaks up into a powder and with water present forms cement,
- Detonations have occurred in the feeding system due to explosive gases entering the feeding pipe, also in the top transport pipe, however, this problem has been solved by a ventilation arrangement which purges the transporting pipe.

Regarding environmental performance, flue gases are cooled outside steel tubes of 8 mm diameter held in bundles of 40 000 where water is condensed. The water is collected and subjected to sedimentation before it is released into the day water system. The water contains approximately 7 kg/m³ of BOD₇ and 25 kg/m³ of suspension material.

Thanks to flue gas cleaning the gas temperature and the particle content in the emitted gas are lowered from 150 to 55°C and from 450 to 47 mg/Nm³, respectively. This is significantly lower than what is stipulated by authority emission regulation limits of 100 mg/Nm³ (measuring) and 150 mg/Nm³ (continuously).

The next generation of gasifiers is known as the Pyroflow gasifiers. They are atmospheric circulating fluidised-bed gasifiers (ACFB) developed in the 1980s to be used with a greater variety of fuels.

6.3 Novel

The background to the technology is the original development by Dr. Ilkka Haavisto at his company Bioneer. The Bioneer company was later sold and after year 2000, Dr. Ilkka Haavisto developed (again with VTT) a new gasifier and gas cleaning system (called Novel) in his company Condens OY. This technology has however now been sold to a not disclosed company.

The construction work for the first Novel plant was completed in April 2005. The commissioning lasted until the end of 2006. However, the gasifier and boiler took only two months for commissioning, from April to May 2005. Gas cleaning and heat recovery was commissioned by the end of August 2005. A photograph of the construction is shown in below Figure.

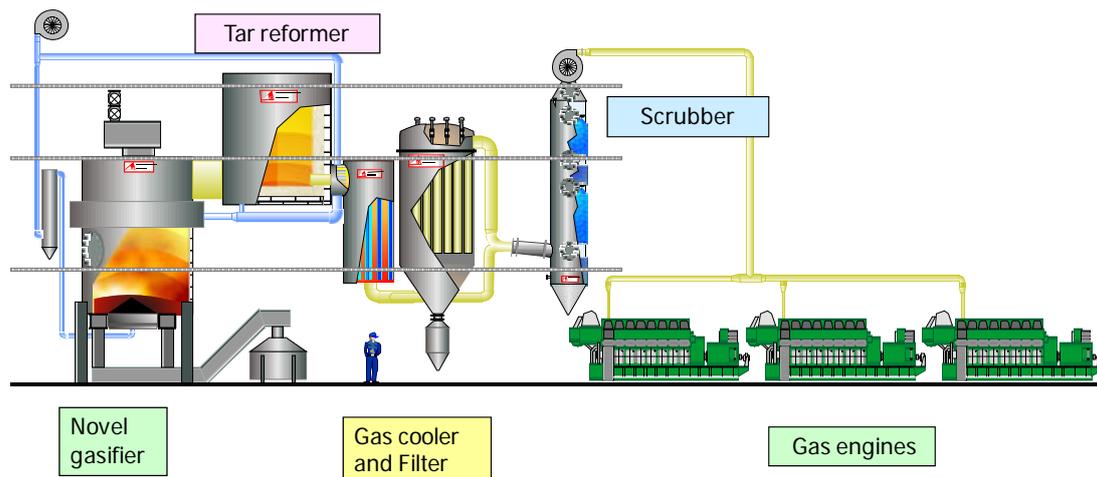


Figur 29. Fotografi av uppförandet av 6 MWf Novel förgasningsanläggningen.

Figure 29. Photograph of the construction site of the 6 MWf Novel gasification plant.

6.3.1 Technology

To make it possible to use the updraft gasifier Bioneer technology for gas engines and other advanced applications Condens OY initiated a development program with VTT based on the experience at VTT with catalytic tar cracking with monolith nickel catalysts (mainly for CFB-gasifiers). The technology was developed at small scale at VTT and tested in a slip-stream in Lahti at the 50 MWf Kymenjärvi I gasification plant.



Figur 30. 7 MW bränsle Novel förgasning kombinerad med kraft och värme vid Kokkemäki, Finland med driftstart under 2005.

Figure 30. The 7 MWf Novel gasification combined power and heat plant at Kokemäki, Finland which was started operation in 2005.

The process scheme for the first Novel plant is seen above. The fuel can be dried in a separate dryer down to 15% moisture to be able to increase the top temperature in the fuel bed to 700-850°C. The high exit temperature is necessary to initially reduce tars (1-4 g/Nm³ tars) and is achieved by adding air above the bed (two-stage operation).

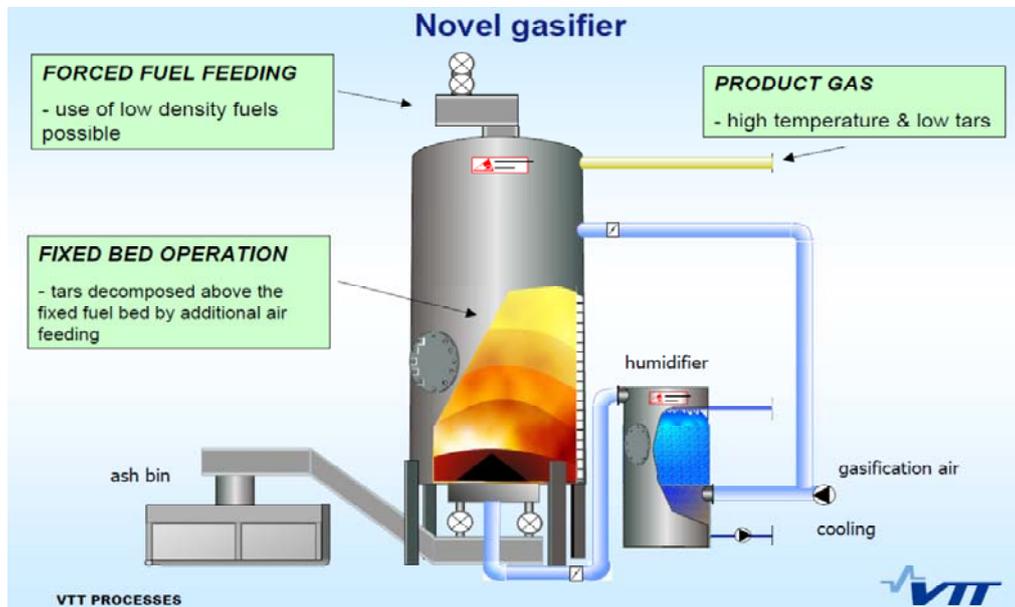
A drawback is that the residual tars are heavier and needs higher temperature on the catalysts. Attempts to treat the full tar load from a normal Bioneer would lead to sever coking on the catalysts. The performance of the gas cleaning process and the equipment used is shown in below Table.

Tabell 4. Gasreningsmetoder och avskiljningsverkningsgrad med Novel-tekniken.

Table 4. Gas cleaning methods and the removal efficiency with the Novel technology.

Impurity	Control method	Content and removal efficiency
Particulates	Bag filters	<10 mg/Nm ³ (>99%)
Tars	Catalytic reformer	<100 mg/Nm ³ (>95%)
Nitrogen compounds (NH ₃ and HCN)	Catalytic reformer and gas scrubbing	<10 mg/Nm ³ (>95-99%)
Sulphur	Low sulphur feedstock and gas scrubbing	<10 mg/Nm ³
Chlorine	Low chlorine feedstock, gas filtering and scrubbing	<10 mg/Nm ³

The gasifier use forced fuel feeding to be able to use low-density fuels. The hot gas is led to the catalyst were the temperature can be adjusted with more air. After cooling/scrubbing with water the gas is fed to a gas engine or a boiler. The total investment was € million.



Figur 31. Schematisk bild på Novel förgasningsreaktorteknologi (Ref. VTT).

Figure 31. Schematic of the Novel gasification reactor technology (Ref. VTT).

6.3.2 Operational experience

Commissioning and operation with one engine continued during 2006 and the two other engines were taken into operation end of 2006 with limited operation hours. The commissioning and first operational period was supervised by staff from VTT who could correct any distortions and the operation was rather smooth. When the advanced staff left, the number of disturbances and operational fall-out increased. This led to severe cost-increase, ultimately to the bankruptcy of the plant developer.

The Bioneer gasification technology was well proven commercially already during the 1980s. The limiting factor for selling further plants was the low oil price. There were additionally extensive pilot testing with a low scale-up factor to commercial size. This explains the success with several commercial gasifiers in only a few years time. Moreover, this provides strong evidence that one-step gasifiers without further gas cleaning can be reliable and rather quickly started-up even with fully automatic operation.

The later experience with the multistep Novel process with advanced gas cleaning illustrate that this is a much more difficult gasification route and needs more time and money for commissioning.

In conclusion, the Novel process data sheet comprises:

- Capacity, 1-10 MWf
 - Suits varying forest fuels and refuse-derived materials
 - Fuel moisture content 0-60%
 - Particle size 0-50 mm
 - Electricity 30-36% and heat 60% of fuel input.

- Demonstration at pilot-scale with:
 - Wood chips, sawdust and shavings
 - Crushed bark, plywood residues
 - Demolition wood, furniture residues
 - Prepared MSW
 - Energy forestry and olive tree residues.

6.4 Värnamo

The Swedish power company, Sydkraft (now E.ON), constructed in the 1990s a co-generation plant at Värnamo, Sweden to demonstrate the Bioflow technology with combined cycle (IGCC) technology. Bioflow, Ltd., was formed as a joint venture (51/49%) between Ahlstrom and Sydkraft in 1992 to develop the pressurized air-blown circulating fluidised-bed gasifier. Foster Wheeler acquired a subsidiary of Ahlstrom that built the gasifier, and Bioflow became part of Foster Wheeler in 1995.



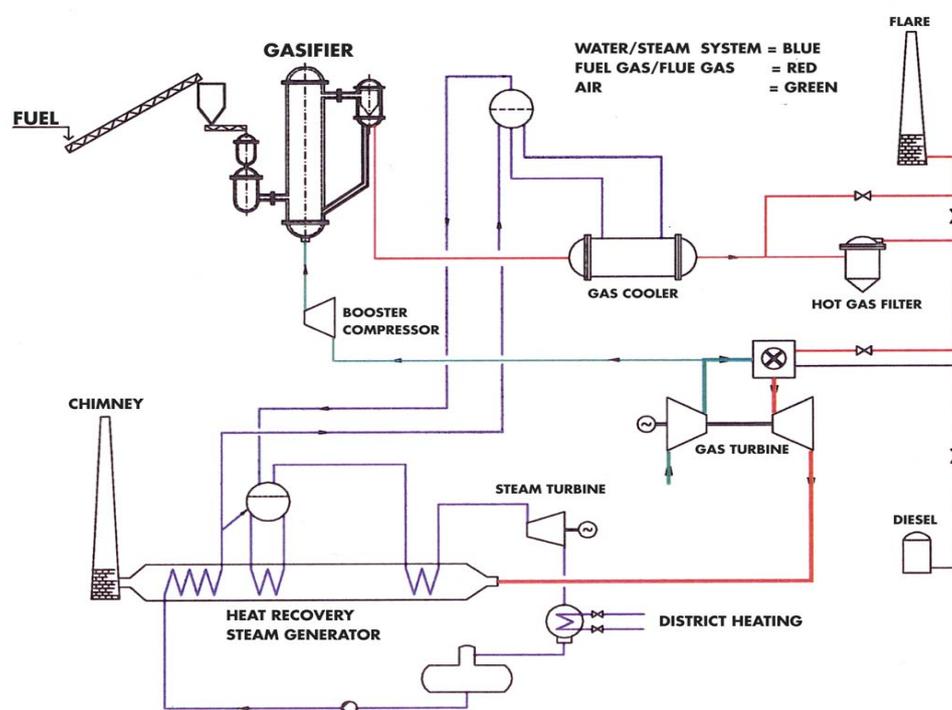
Figur 32. Foto av Värnamo BIGCC anläggningen (Ref. Foster Wheeler).

Figure 32. Photograph of the Värnamo BIGCC plant (Ref. Foster Wheeler).

The biomass integrated gasification combined cycle (BIGCC) plant in Värnamo was commissioned in 1993 and fully completed in 1996 and mothballed in 2000. Then it was planned to be reconstructed for synthesis gas production by VVBGC who acquired the plant and the technology rights.

6.4.1 Technology

The Värnamo plant was the world's first complete BIGCC power plant, which utilised wood as fuel. The plant is located in Värnamo and the technology used in the power plant is based on gasification in a pressurised circulating fluidised bed gasifier. The technology was developed by Foster Wheeler Energia Oy in co-operation with the former Sydkraft AB. The Figure below show first a schematic of the BIGCC process.



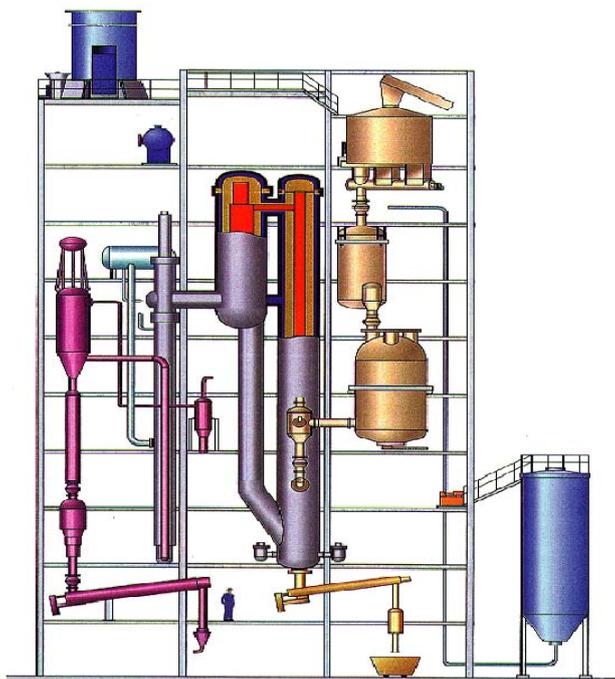
Figur 33. Schematisk bild över Värnamo Bioflow BIGCC processanläggningen (Ref. E.ON).

Figure 33. Schematic over the Värnamo Bioflow BIGCC process plant (Ref. E.ON).

The plant at Värnamo was a demonstration plant, which produced about 6 MWe to the grid and 9 MW of heat to the district heating system, from a total fuel input equivalent of 18 MWf. The start-up phase was completed during spring 1996 and following that a demonstration programme was launched, which was continued until June 2000.

The accumulated operating experience amounts to about 8500 hours of gasification runs and about 3600 hours of operation as a fully integrated plant as per the end of 1999. The test runs were very successful and the plant was operated on different wood fuels as well as straw and RDF. One of the last tests included operation on 100% straw, which was accomplished without disturbances or problems.

The Värnamo gasifier is of a rapid CFB type and initially dolomite limestone was used as bed material. Later on experiments were made with magnesium oxide for a catalytic tar cracking effect however the results are mixed. The temperature is high, 950 oC in that tar forming is suppressed. Moreover, the gas is heat exchanged in a special type of heat exchanger where the temperature is lowered to 350°C in that alkali shall condense on the particles and be filtered in the hot gas filter. The clean gas is then fed to the gas turbine.



Figur 34. Schematisk bild av demonstrerad process i Värnamo (Ref. Foster Wheeler).

Figure 34. Schematic of the process as demonstrated in Värnamo (Ref. Foster Wheeler).

Nitrogen oxide levels are high; thus the gas needs to be treated afterwards. An alternative is selective catalytic nitrogen reduction of the ammonia before the gas burner. Interestingly, in the late days of operation they tested several types of biomass and at one point they fed the gasifier with 100% straw and achieved full syngas gas turbine operation without problems.

The process is centred on the atmospheric CFB gasification system which consists of a gasification reactor, a cyclone to separate the circulating-bed material from the gas, and a return pipe to return the circulating material to the bottom part of the gasifier. All these components are entirely refractory-lined. From the cyclone, the hot product gas flows into an air preheater located below the cyclone.

Gasification air is blown with a high-pressure air fan through an air distribution grid at the bottom of the reactor, below a bed of particles. The air velocity is high enough to fluidize the bed particles and convey some of them out of the reactor and into the cyclone, where most of the solids are separated from the gas and returned to the lower part of the gasifier. Both the gas and solids are extracted from the bottom of the cyclone.

The circulating solids contain char that is combusted with the fluidizing air, generating the heat required for the pyrolysis process and subsequent, mostly endothermic, gasification reactions. The circulating material also serves as a heat carrier and stabilizes the process temperatures. Coarse ash accumulates in the gasifier and is removed from the bottom with a water-cooled screw.

6.4.2 Operational experience

1993-1999

The Värnamo gasification plant was in operation during 1993 and 1999 and was then mothballed in the year 2000, when the plant economics were not favourable and the demonstration program had finished the verification of the technology. In total about 8500 hours of operation was logged for the gasifier and 3600 hours with combined cycle integration.

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.

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

Due to the relatively low combustion temperatures in the gas turbine combustors when burning product gas, thermal NO_x was very low. Total NO_x 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 NO_x. The recorded levels of alkalis were below 0.1 ppm wt.

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 1200 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 and a chemical attack was excluded. By this time, a weight-support grid was installed below the main filter. However, since the installation of this grid a tendency of bridging has been observed (build-up of a deposit layer between the filters), and this was not observed earlier.

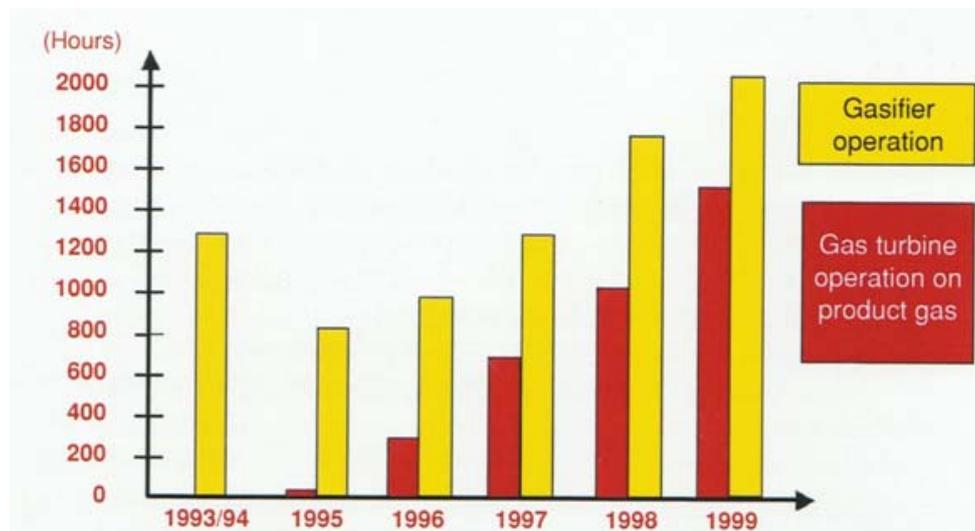
As a result of the breakages of the main filter the gas turbine, and later as well the replacement gas turbine, were sent back to the supplier for repair. In order to overcome a similar problem in the future a metallic police filter was installed downstream of the main filter. Rather soon after this installation was completed another failure of the main filter occurred. Noteworthy, is that the measured pressure drop over the main filter was not changed significantly. However the pressure drop over the police filter increased rapidly during this time and thus the breakage could be detected.

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. This replacement of a ceramic candle filter with a metallic filter also occurred in the IGCC Wabash IGCC Project, USA where they experienced the same type of problem. The metal filter, like the ceramics, showed very good filtration efficiency, with stable pressure drop. This filter has been in operation for more than 2500 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.

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 3600 hours as a fully integrated plant was on 100% gas for the LCV gas from 40% to full operating load.



Figur 35. Drifftimmar mellan 1993 och 1999 i Värnamo (Ref. Sydkraft).

Figure 35. Operating hours between 1993 and 1999 in Värnamo (Ref. Sydkraft).

Complete combustion of the hydrocarbons was always achieved with emissions between 1 and 4 ppm only, whereas a slightly high value of CO was observed with values up to and sometimes even above 200 ppm on part-load operation. As mentioned before, levels of NO_x 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 NO_x, 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 residues, 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.

The conclusions from the demonstration program are the following. 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 3600 hours with the gas turbine operating solely on product gas produced by the gasifier. Huge experience was gained from more than 8500 hours gasifier operation. Principal results achieved are:

- 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 plants.

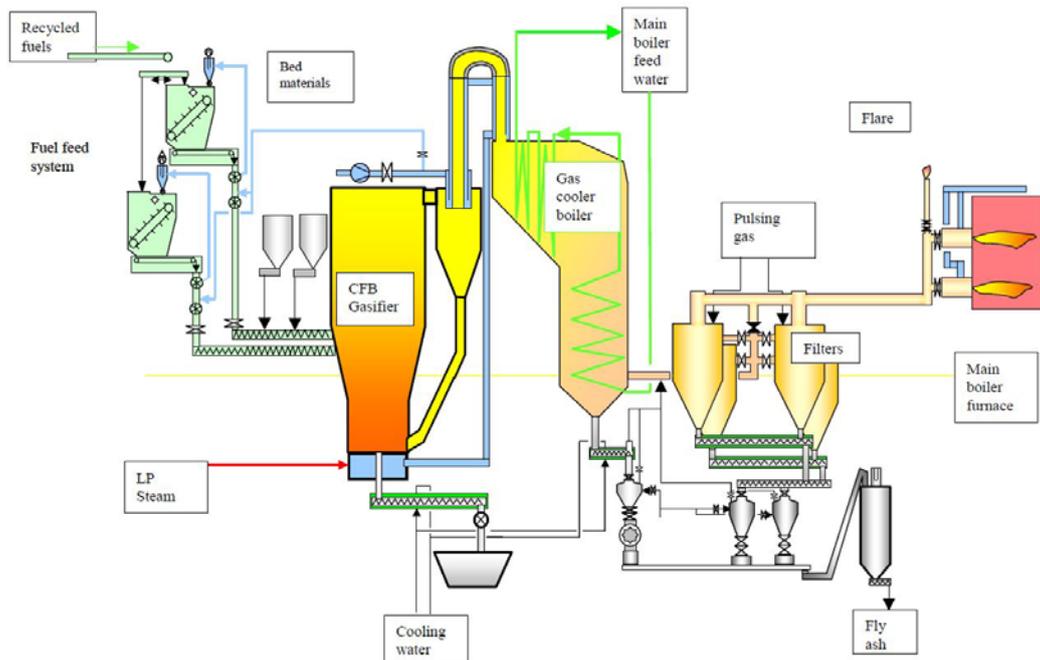
During the demonstration program many problems were solved with the operational experience but some were postponed to further developments. One of the economically more significant ones was the high throughput of bed material. For a full-scale plant this would be too costly and lower the efficiency. Suggestions were made to recover bed material from the bottom ash.

The high bed turnover was probably why even difficult fuels from a sintering point could be fed without significant problems. Still, the evaluation of a full-scale plant indicated that it would not be commercially interesting without special pricing or other subsidies.

2004

A new project was started in 2004 with a retrofit of the plant to a syngas application for a clean hydrogen-rich synthesis gas with pure oxygen as oxidant. The gasifier was rebuilt and re-started but the project was later cancelled as the necessary investment funds could not be accomplished.

The work scope included improvement of the feeding system with less use of inertization gas, installing of a high temperature filter and a methane & tar reformer unit with a gasifier retrofit to oxygen-blown fluidised bed.



Figur 37. Schematisk bild av Foster Wheelers atmosfäriska CFB förgasarkoncept för RDF (Ref. Foster Wheeler).

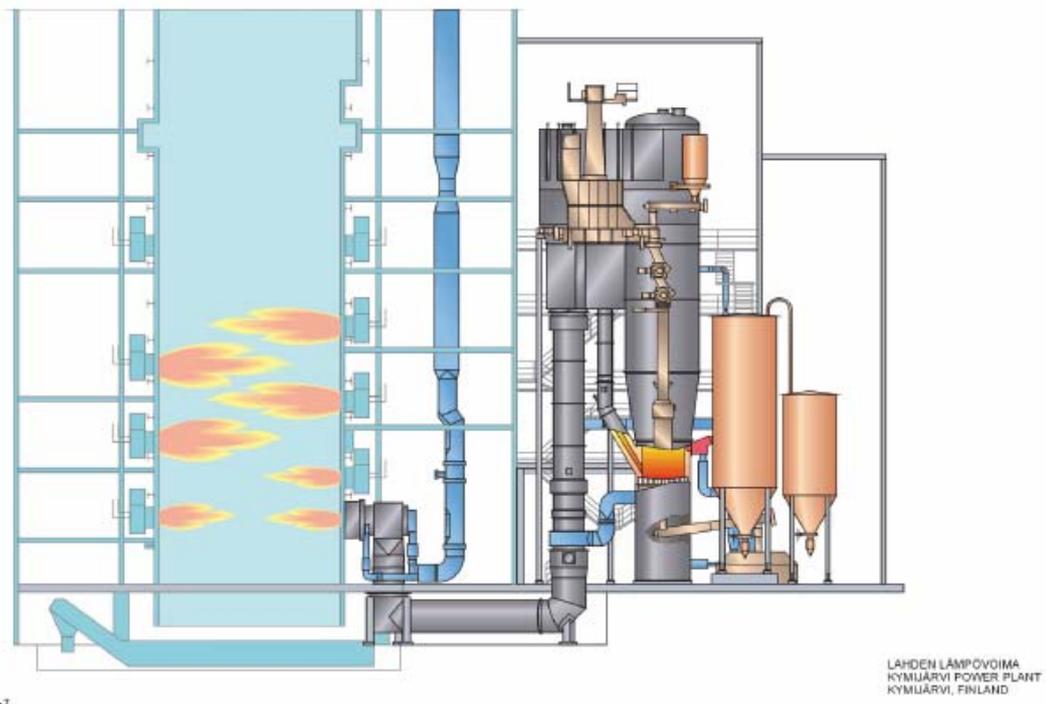
Figure 37. Schematic of the atmospheric Foster Wheeler CFB gasifier concept for refuse-derived fuels (Ref. Foster Wheeler).

A large gasification system reference delivered is the 50 MWf Lahti gasifier plant, which have a reported availability of 97.5%. The accumulated biomass fuel is 400 000 tonnes and they have been operating 27 000 h (until 2004).

The operating experience of the gasifier during the years 1998-2002 has been excellent. On annual basis, the gasifier availability has been between 96.1-99.3% according to the supplier. With regard to the gasification plant itself, the few problems have been related mostly to the use of shredded tires as a fuel in the gasifier. On several occasions the wire content of tires (there is no additional separation of metal wires with magnet after shredding) was so high that accumulated wires blocked the ash extraction system and the gasifier had to be shutdown. Otherwise, with all other fuel fractions, the operation of the gasification process was good.

Concerning the gasification process itself, the results have met the expectations. The operating conditions as regards temperatures, pressures and flow rates have been as designed and the process measurements as regards the product gas, bottom ash and fly ash composition have been very close to the calculated values. Due to the high moisture content (up to 58%) of the gasifier fuels, the heating value of the product gas has been low, typically only 1.6-3.2 MJ/Nm³.

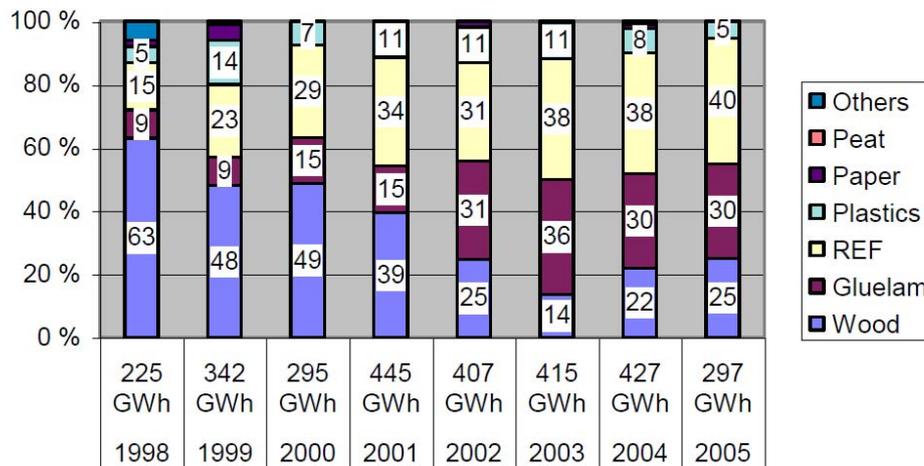
They also tested gas cleaning for a few years, taking a 5% slip-stream which they cleaned with monolith catalyst to demonstrate methane and tar cracking.



Figur 38. The Foster Wheeler Lahti CFB gasifier (Ref. Foster Wheeler).

Figure 38. The Foster Wheeler Lahti CFB gasifier (Ref. Foster Wheeler).

The gasifier has operated well with varying fuel mixes, with availabilities of 96% or higher. The Figure below shows the fuels used and energy produced in 1998-2005 and the Table the annual availabilities 1998-2001.



Figur 39. Använda bränslen och produkter i Lahti 1998-2005 (Ref. Foster Wheeler).

Figure 39. The fuels used and energy products in Lahti 1998-2005 (Ref. Foster Wheeler).

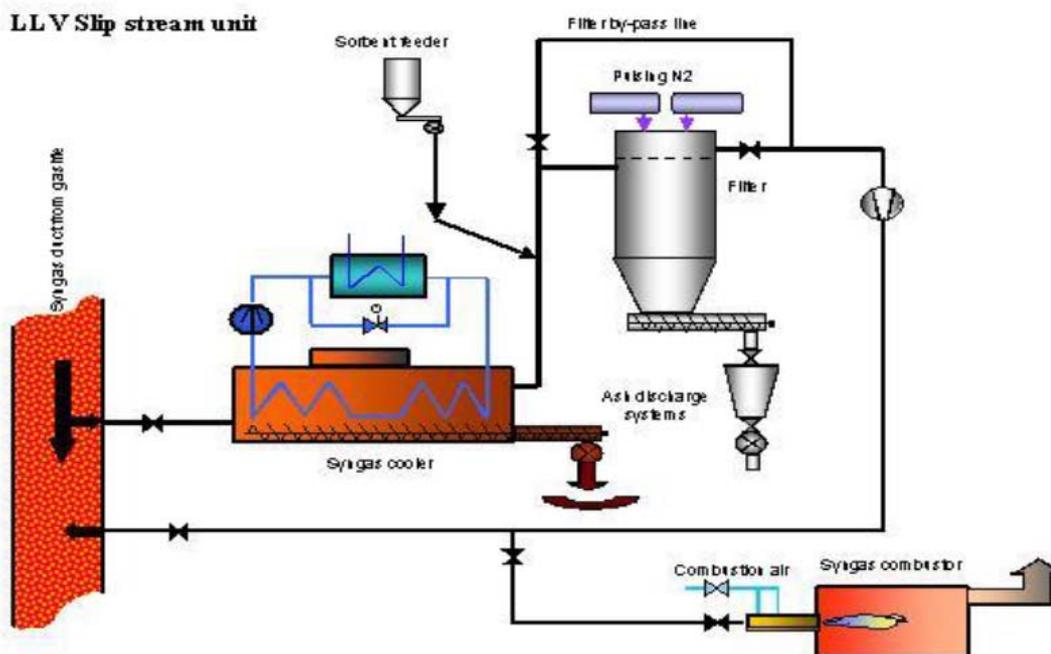
Tabell 5. Årlig drifttillgänglighet vid Lahtiförgasaren mellan 1998-2001.

Table 5. Annual operating availabilities of the Lahti Gasifier 1998-2001.

Operation year	Availability	Comment
1998	99.3%	Second half of the year.
1999	98.9	
2000	97.1	
2001	96.1	

A slipstream process was constructed at the Lahti CFB gasifier for long-term testing of the gas cooler and product gas filter in realistic conditions, with product gas generated in normal operation of a commercial-scale gasifier running on waste- and wood-based fuels. The objectives of this project were to test the pieces of equipment in a commercial-type operating environment and generate data on the availability and performance of the system.

The Figure below shows an outline of the slipstream test unit consisting of the following equipment: Syngas cooler including ash removal system, hot gas filter with ash removal/recycling system, syngas fan, syngas combustor and auxiliary equipment (nitrogen system, additive feeders).



Figur 40. Schematisk bild av sidoströmtesten (Ref. Foster Wheeler).

Figure 40. Schematic of the slip-stream tests (Ref. Foster Wheeler).

The process conditions were fully representative of those which would be expected in “normal” operating conditions. Generally, the gasifier fuel was a mixture of wood and waste (REF), typically about 40% waste and 60% wood-based fuel. Additionally, tests with up to 100% waste were carried out to study syngas combustion and the emissions formed in the combustion of waste derived syngas.

Typically about 5% of the total syngas flowing from the 40-70 MWf CFB-gasifier to the main boiler was extracted to the slipstream unit. In the gas cooler, syngas temperature was decreased to the filtration temperature. After the hot filter, a fan provided with frequency converter for flow-rate control increased syngas pressure, and the gas was led back to the main gas line or to syngas combustion.

The slipstream unit was operated from March 14, 2003, to April 26, 2004, for a total of 3346 hours. In general, the long-term testing was smooth and major problems did not occur. Most of the interruptions of the slipstream testing were caused by malfunction of auxiliary equipment. Problems in the main equipment, syngas cooler and hot filter, caused few interruptions. Generally, they worked reliably.

In the filter unit, different filter elements were tested in parallel: 3M’s glass fiber bag filters with ceramic coating and rigid low-density candle filter elements supplied by Tenmat (calcium silicate) and Madison Filter (aluminum silicate). The filtration temperatures varied from 320 to 400°C during the tests. The separation efficiency of the filter was excellent, with dust contents below 10 mg/Nm³ measured downstream of the filter.

None of the tested elements of any type failed in service, and also after the testing all the elements were found to be intact. During the long-term testing, the syngas cooler worked properly the majority of the time. The hampering tar condensation on the cooling water tubes can be avoided by adjusting the temperature of the cooling water to the right level. Only a thin tar layer condensed on the surfaces of the water tubes.

The syngas cooler was kept clean with Foster Wheeler spring hammers and typically, the cooling water tubes were kept quite clean even with infrequent operation of the spring hammers. The excellent operation of the gas cooler and the spring hammering was confirmed in the inspection made after the testing was completed: Some ash deposit was found between the spaces of the cooling water tubes, but this was only in the first cooling element, which was known to be at too high temperature from the very beginning.

In addition to the long-term testing, syngas combustion tests were carried out in order to study the emissions in filtered syngas combustion. Syngas was co-combusted in a separate boiler with natural gas in combustion tests done in October-November 2003. Four syngas combustion test runs were performed with three different gasifier fuel mixtures of biomass and REF: 60/40, 30/70, 0/100.

The following summarizes the experiences: most of the heavy metals were in solid phase at the syngas filtration temperature and thus they can be captured from syngas to the filter ash. Above 99.9% of the fuel heavy metals can be removed to ashes. Mercury is in gas phase and it cannot be removed by filtration. The mercury content of flue gas is thus dependent upon the fuel mercury content. An additional process step will be able to capture mercury.

The limit values of heavy metals set by the EU's Waste Incineration Directive (WID) were easily met. In clean syngas combustion PCDD/F compounds did not form. The total content of dioxins and furans was only 0.00002-0.0004 ng/Nm³ I-TEQ, while the WID emission limit is 0.1 ng/Nm³ I-TEQ. About 80% of chlorine retention to ashes was achieved by normal limestone addition to the gasifier and syngas filtration.

With calcium hydroxide [Ca(OH)₂] feeding before the filter, chlorine retention was increased to above 95%. Sulphur retention to ashes was moderate. Most of the fuel sulphur appears in flue gas in gaseous phase and complete sulphur retention would require separate flue gas cleaning, because calcium-based sulphur retention is equilibrium limited in gasification.

While the product gas has been reported to contain dust and tar, alkali, ammonia, and HCN, performance has not been adversely affected. In corrosion probe monitoring tests of the boiler, no indication of abnormal deposit formation, fouling or corrosion could be seen. Inspection of the boiler heat transfer surfaces (furnace walls, superheater, economizer and air preheater) showed no abnormal deposit formation or high-temperature corrosion.

Stability of the steam cycle, coal burners and product gas burners has been excellent. The large openings made to accommodate the product gas burners have caused no disturbance in the water circulation.

Operation of these burners has been good: combustion of the low-Btu, high-water content product gas has been stable. Operating temperatures, pressures, flows and gas compositions were very close to design values. Because of the excellent process behaviour of the gasifier and low impact on emissions, Finnish authorities have set no limitations on applicable feedstocks or utilization of ash (very low trace metal leachability). All fuel fractions that have been tested in the gasifier are currently permitted by the Finnish regulators to be used at the plant.

Due to fuel shortages and problems in the fuel preparation plant at times during the first year of operation, the gasifier was occasionally operated in the combustion mode. In this mode, normal temperatures (840-850°C) are maintained in the gasifier while the fuel feed rate is minimized to 5-7 MWf.

Use of shredded tires as gasifier fuel has caused operational problems. Because there is no magnetic separation after the shredder, accumulation of tire wire occasionally blocked the ash extraction system, resulting in gasifier shutdowns. Other problems have included faults in fuel reception, fuel feeding, automation, and fuel quality and particle size. These have all been corrected satisfactorily.

6.6 Corenso

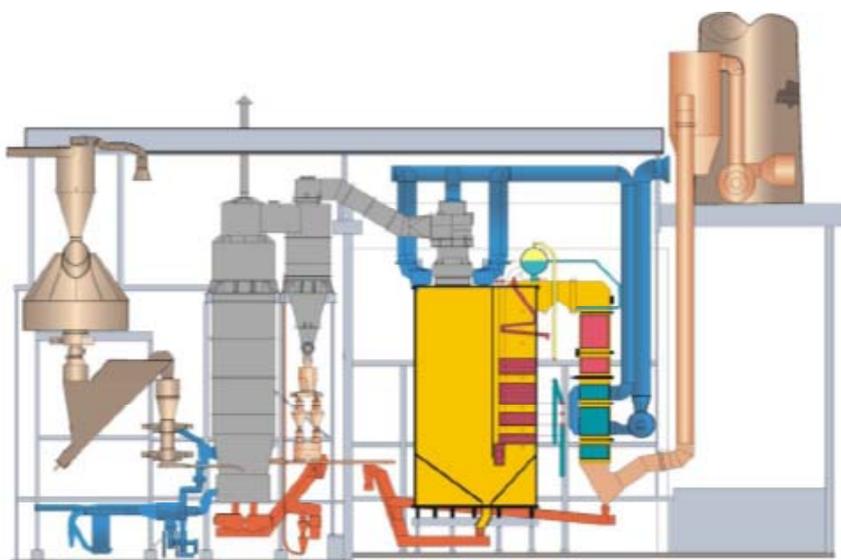
In Europe, about 1 million tonnes of liquid carton board is consumed annually. The majority of this still ends up in landfills due to the lack of collecting systems. Additionally, until now, there have been difficulties in utilizing the remaining mixture of plastics and aluminium in energy production. A new concept was developed based on BFB gasification technology capable of generating power from plastics and recovering aluminium and the world's first plant was built in Varkaus, Finland.

6.6.1 Technology

Originally, the liquid packaging board recycling plant was opened at the end of 1995 at Corenso United Oy Ltd's core-board mill in Varkaus. The mill's fiber recycling plant separates used liquid packages and wrappings into their components: separated wood fiber is used for core-board production and, formerly, the remaining mixture of polyethylene plastics and aluminium would be incinerated in a boiler.

However, incineration of this mixture in a normal boiler proved to be very problematic due to the aluminium forming deposits on the heat transfer surfaces and on the grid of the boiler. These layers had to be removed at regular intervals, which caused interruptions in the power production and decreased the availability.

In order to overcome the problems, a new concept based on BFB gasification was developed by Corenso United Oy Ltd with Foster Wheeler and VTT. The process development work started at VTT's test laboratory in 1997, followed by a 15 MWf demonstration-scale gasification plant built by Foster Wheeler at Stora Enso's Varkaus mill. During the tests this demonstration plant was operated for a total of 1400 hours.



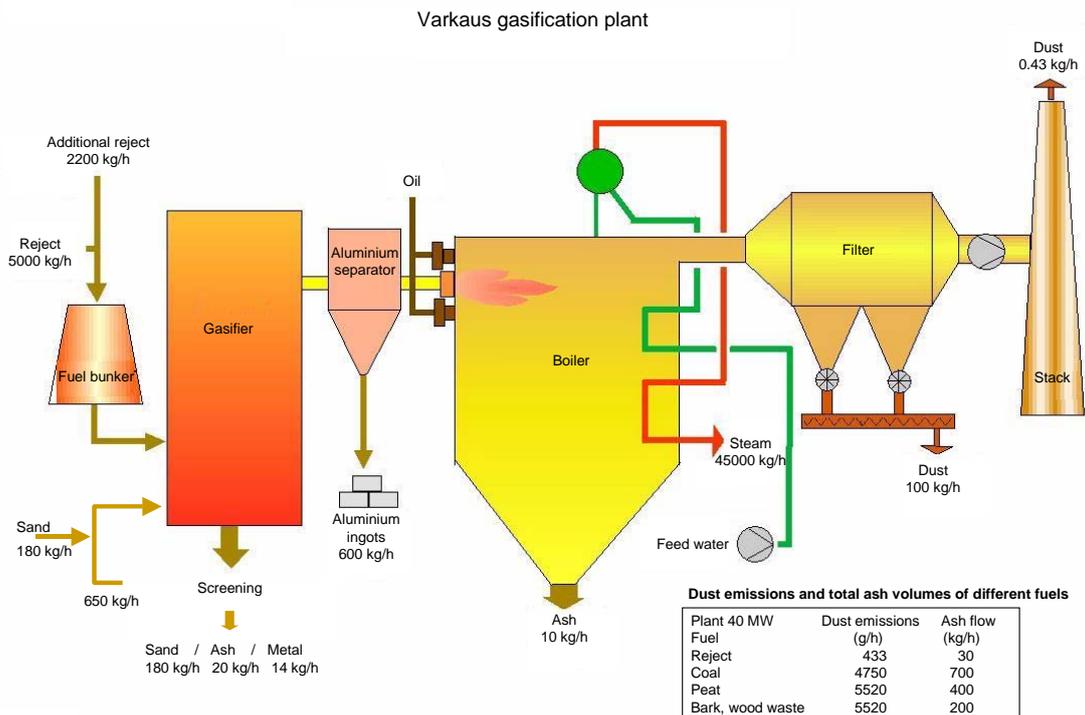
Figur 41. Schematisk bild av Corenso återvinningsanläggning (Ref. Foster Wheeler).

Figure 41. Schematic of the Corenso recycling gasification plant (Ref. Foster Wheeler).

The development work resulted in construction of a full-scale gasification plant at the Stora Enso Varkaus mill by Foster Wheeler, the plant having an output of 40 MW, generating 165 GWh/year of syngas energy and recovering and recycling more than 2100 tonnes/year of metallic, non-oxidized aluminium.

6.6.2 Operational experience

The gasification plant shown in Figure below has been in operation approx. 23 000 hours (December 2005).



Figur 42. Corenos Varkaus-anläggning med återvinning av multi-materialförpackningar (Ref. Foster Wheeler).

Figure 42. Corenso's Varkaus plant with recycling of multi-material packaging (Ref. Foster Wheeler).

6.7 Varkaus

In 2008 Foster Wheeler was awarded a contract by NSE Biofuels for a 12 MWf demo-scale circulating fluidized-bed (CFB) biomass gasifier to be located at Stora Enso's mill in Varkaus, Finland. NSE Biofuels is a 50/50 joint venture by Stora Enso Oy and Neste Oil.



Figur 43. Foton under uppförande av pilotanläggningen vid Stora Ensos Varkaus Bruk med atmosfärisk, syrgasbläst biomassaförgasning med djupgasrening och sidoström med Fischer-Tropsch dieselproduktion (Ref. Stora Enso).

Figure 43. Photos during construction of the pilot demonstration plant at the Stora Enso Varkaus mill of atmospheric, oxygen-blown biomass gasification with deep gas cleaning and slipstream with Fischer-Tropsch diesel production (Ref. Stora Enso).

6.7.1 Technology

The initial development started at VTT's lab in 1997 and was designed for a wide range of different biomass feedstock followed by novel catalytic gas reforming technology. The work aimed at intermediate-size plants of 200-300 MWf. The first phase with a process plant of 0.5 MWf was started in 2009, and operated 1400 hours until closure. The development focus was on the front end: biomass handling, gasification and ultra-cleaning of gas to meet the specifications of the production processes.

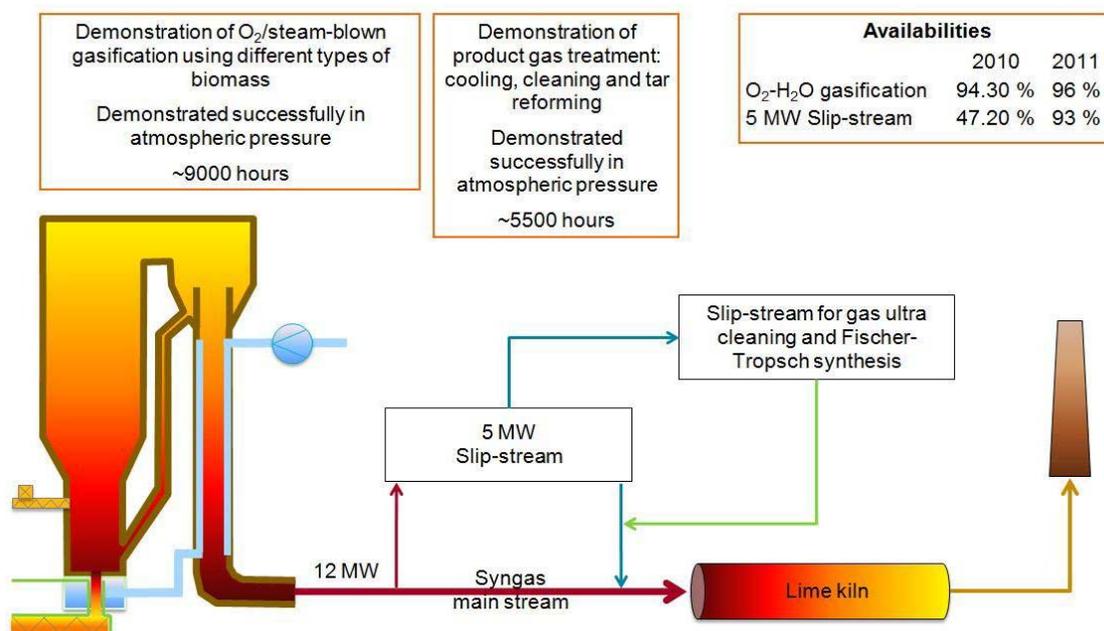
The second step in the development path was a long term demonstration in a larger scale. Together with Foster Wheeler, Finnish joint-venture NSE Biofuels built a demonstration plant in Varkaus, Finland, to demonstrate long term gas production and gas cleaning to meet the requirements of FT-synthesis.

Gas for the gas cleaning test plant was produced in an atmospheric oxygen-steam blown CFB gasifier, which also supplied, and still supplies today, gas for the lime kiln of the Stora Enso pulp and paper mill. Gas produced in the gasifier is referred to here as “raw gas” to make a clear difference between cleaned and reformed gas, which is referred to as “product gas”.

The gasifier is a 15 MWf atmospheric circulating fluidized bed unit, which started operation in the end of 2008. It started first as an air-blown gasifier in order to produce only raw gas for the lime kiln. In 2009 the gasifier was operated for the first time using a mixture of oxygen and steam as the fluidizing agent. Since then the gasifier was mainly operated in the oxygen-steam mode to produce high calorific and low nitrogen content gas for the 5 MWth gas cleaning demonstration plant. The whole process chain of the plant is shown in Figure below.

6.7.2 Operational experience

Foster Wheeler supplied gasifier with auxiliaries and some of the main equipment for the gas cleaning plant: gas coolers, hot gas filters, ash handling systems and the scrubber. Foster Wheeler also executed the majority of the process design including the control system. Process design of the reforming unit and the complete design of further gas ultra cleaning and the integration of a 0.1 MWth FT test unit were taken care of by NSE.



Figur 44. NSE Biofuel processlayout av Varkausanläggningen (Ref. Foster Wheeler).

Figure 44. The NSE Biofuel process layout of the Varkaus plant (Ref. Foster Wheeler).

The test runs were carried out to optimize the gasifier process parameters for producing good quality raw gas for the follow-up process. Tars, light hydrocarbons, HCN, NH₃, H₂S and COS and fly ash/particulates were analyzed from the raw gas, as well as the gas main components CO, CO₂, H₂, CH₄ and H₂O. Carbon conversion of the gasifier was also determined.

Test runs included testing at different gasification temperatures ranging from 860 to 940°C and different oxygen/steam ratios. The oxygen content of the fluidizing agent into the wind box was varied between 23% and 50%-w, typical value being around 45%-w. The fuel consisted of different types of woody biomass: wood chips, first felling wood, bark and forest residues.

The essential objectives of the gas cleaning test runs in Foster Wheeler's scope were to demonstrate the performance of the gas coolers and the hot gas filters in long-term operation and to determine the design basis for this equipment. The cumulative operation hours of the oxygen-steam gasification were more than 9000 hours by the beginning of June 2011 and for the slip-stream gas cleaning plant the operation hours were more than 5500 hours. The plant thereafter was closed and the cooperation ended.

In conclusion, the plant demonstrated successfully biomass gasification with production of a clean synthesis gas at larger scale and synthetic diesel in small-scale at continuous operation.

7 Meva Energy

7.1 Background

Meva Energy is a small company based in Göteborg, Sweden which develops and commercializes a biomass gasification technology that converts biomass to a renewable syngas for heat and power production.

The originating company Meva AB was founded in 1939. The activities of Meva AB have been development, sales and servicing of energy efficient electromechanical equipment for the energy, mining, steel, pulp and paper industries.

Meva Energy offers a standardized biomass gasification system called the Vortex Intensive Power Process (the VIPP-system), which is designed to produce syngas, from solid biomass, for example wood residue. The syngas is intended for combined heat and power generation (CHP) in a small-scale (0.5-5 MWe) power plant.

The VIPP technology originates from the developments of Prof. B. Kjellström of Luleå Technical University. This experimental unit was extended to a full pilot plant at ETC and has a thermal input of 500 kW and includes the gas cleaning process and an engine of 100 kW output. It has been operated for development purposes on crushed wood pellet fuels for 800 hours in total; the longest uninterrupted operational time is 12 hours.

The engine used has been supplied by Cummins and Meva Energy has entered into a co-operation with this engine manufacturer. During the spring of 2012, fuel tests with fuels other than woody biomass took place in the pilot plant.

In 2006, Meva Innovation acquired the rights for the cyclone gasification technology. Since then, the experimental gasifier has been extended to a full pilot plant used to verify the process and will also be used for future R&D.

A scaled-up plant of 1.2 MWe and 2.2 MW heat was contracted by Pite Energi in mid 2010 to replace an oil-fired installation in the village of Hortlax outside Piteå. The fuel is crushed wood pellets. Commissioning started in May 2012.

7.2 Hortlax

7.2.1 Technology

The VIPP-system (Vortex Intensive Power Process) is a small-scale combined heat and power system based on the gasification of biomass fuels for small-scale cogeneration. The electricity is produced in a gas engine or in a gas turbine. In addition, heat is effectively recovered from the gasification system as well as from the engine.



Figur 45. Foto av Meva Energys anläggning i Hortlax (Ref. Meva Energy).

Figure 45. Photo of the Meva Energy plant at Hortlax (Ref. Meva Energy).

The core of the system is the cyclone gasifier. The gasifier is fed with pulverized fuel by means of the gasification air. The fuel can be softwood, chips or pellets, with app. 10% moisture. Average particle size must be less than 0.8 mm. The cyclone gasifier is operated between 800-900°C. Downstream of the VIPP gasifier, the VIPP-ECP (Evidential Cleaning Process) cleaning process is used to achieve the quality standard required for use in the current application.



Figur 46. Hortlax processlayout för Meva Energy VIPP process (Ref. Meva Energy).

Figure 46. The Hortlax process layout of the Meva Energy VIPP process (Ref. Meva Energy).

As clean fuel gas is targeted for the operation of gas engines or gas turbines, only low levels of tar and particles are accepted in order to prevent damage to these prime movers. VIPP-ECP consists of a three stage cleaning process where the raw gas first passes through a cyclone for separation of coarse particles, then a scrubber operating with an organic oil and then, as a final step, a wet electrostatic precipitator (WESP) to obtain a guaranteed pure fuel gas.

A bleed of oil, into which also the particulate fines are trapped, has previously been re-injected into the gasifier. The temperature is kept above the dew of water vapor. The fuel gas is then fed to a turbo-charged ICE. It is claimed that an efficiency of 30 and 50%, to power and heat, respectively can be obtained based on a pretreated (dried and pulverized) fuel.

7.2.2 Operational experience

The scaled-up demonstration plant was commissioned in 2012 in Hortlax. It is fuelled by wood chips or pellets producing 1.2 MWe and 2.2 MW of heat. The plant uses exactly the same technology as a pilot plant but scaled up by factor of about nine. In this installation, a 9.1 litre Cummins V18 engine is the prime mover.

The cyclone gasifier technology can rapidly adjust its production, which is a key feature for future integrated renewable energy systems. The pellet silo storage is 39 tonnes and lasts about 35 hours of operation. The fuel is fed in cells with a blower where the air to fuel ratio is measured to control the gasification. The fuel feeding system has been redesigned. The pressure is about 0.3 bars over-pressure.

The gasifier is first started with an oil burner to 600-700°C. In the gasifier the residence time is short and it is critical to maintain a high temperature in order to minimize pyrolysis and large content of tars.

There has been build-up of deposits in the cyclone and the aim is to trim the operation to minimize these also on the heat exchangers. As these were originally under-dimensioned they have been replaced. The build-up problem has recently been solved. The cause was poor feedstock grinding and a substantial portion of the feedstock being in fractions over the specification of 1 mm. With better feedstock control Meva Energy has minimized the build-up problem.

The gas composition has been very stable. The gas is cleaned in a RME scrubber from tars. However, the high temperature early on in 2013 caused evaporation of the oil and causes in turn coking in the nozzles. This has been solved and is thus not longer the case with the introduction of a more efficient gas cooler.

The tar are absorbed and dissolved in the RME and today, the biooil is sent for destruction. The Wet Electro-Static Precipitator (WESP) which removes tar is cleaned in a cycle with spray of RME. A process change is the new centrifuge for tar removal, introduced in the spring of 2014 and has operated well. In addition, the flue gas coolers have been replaced for tube heat exchangers.

The plant can be operated by one man but has so far been operated by two operators. The long term goal is to operate the plant without continuous supervision. The plant is kept warm during the night and currently optimized for high availability with main issues including ash retrieval and the process temperature in the gasifier. The process is run in campaigns but longer campaigns have not earlier been possible as the ash removal is been inadequately dimensioned which hampered the prolonged operation. Since October 2014 there was the introduction of better ash removal capacity which eases this earlier constraint.

The plant has been operated for a few hundred hours with the gasifier and much less with the integration with the gas engine. The design availability is 8000 hours per year but one constraint with the plant is the building as the process had to be fitted for an existing building and thus it is troublesome to make repair and changes of equipment.

Since October 2014 the Hortlax plant is operated in longer campaigns than ever before and the prospect of initiating 24-h operation in the near future looks good. This information is based in November from the supplier and not the authors own analysis.

There is 100% redundancy for the heat plant as an oil-fired boiler is still at the site for operation if the gasification plant is not operating. The district heating temperature is 73°C with a return of 55°C.

8 Ortner

8.1 Background

The Ortner Gruppe is an Austrian conglomerate with a group of companies in the construction industry with buildings for industry and production as well as general buildings. In addition they build plants with sewage and environmental technology, chemical and pharmaceutical industry etc.

8.2 Oberwart

The 8.5 MWf biomass gasification CHP plant at Oberwart, Austria producing 2.7 MWe and max 4.1 MWth heat, was built for Energie Burgenland. The plant is similar in design to the Güssing plant, taking in 53 ODT/day of wood.

However, in 2004 when Repotec GmbH and the utility BEGAS were negotiating the hours guaranteed in the contract, BEGAS ended up giving the contract to Ortner (a combustion installer) but without requesting a co-operation with Repotec. Ortner went on to build the plant, with heavy cooperation from TÜV. Construction finished in 2007, commissioning was ongoing in Nov. 2008.



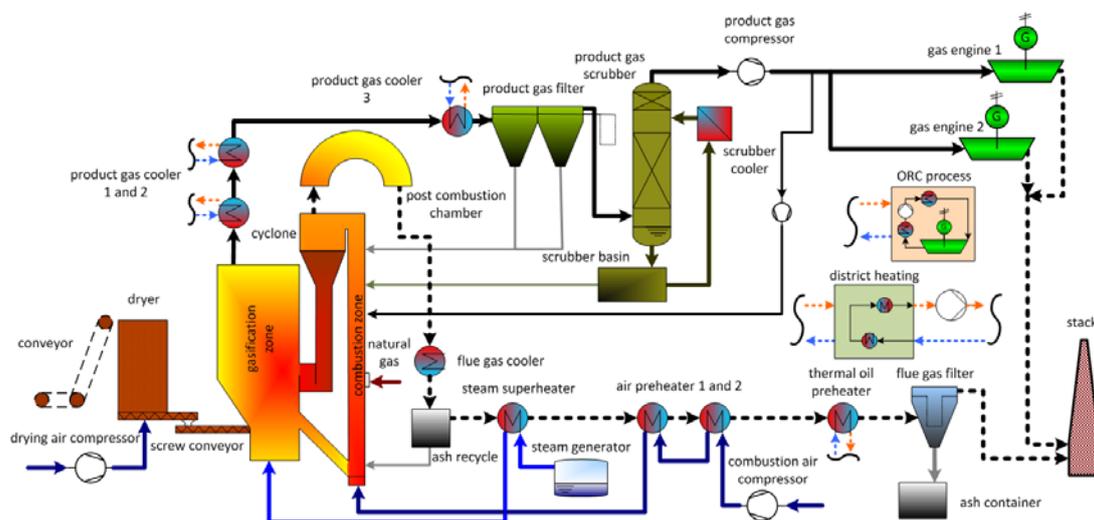
Figur 47. Foto av Ortners anläggning i Oberwart (Ref. Ortner).

Figure 47. Photo of the Ortner plant at Oberwart (Ref. Ortner).

8.2.1 Technology

The overall concept for the gasification plant is the same as for the Güssing plant with Repotec. Therefore the reader is advised to see this chapter for the specific technology in gasification. The downstream processes will be explained from here on.

- Technology: dual zone fluid bed biomass gasification gas engine and ORC process, with peak-load natural gas
- Fuel thermal input ca. 8.5 MWf
- Electrical output gas engine max. 2.4 MWe
- Electrical output ORC process max. 0.35 MWe
- Heat power max. 4.1 MWth
- Annual wood chip fuel requirement 23 000 tonnes, air-dried
- District heating transmission route 5300 m
- District heating system temperature: feed 95°C / return 65°C.



Figur 48. Processlayout av KWK Oberwart (Ref. Energie Burgenland).

Figure 48. The process layout of the plant at KWK Oberwart (Ref. Energie Burgenland).

The plant uses gas cooling and gas clean-up in a bag filter followed by a tar scrubber. The cooled and cleaned producer gas is fed into two gas engines for power generation. In addition there is a biomass drying unit and an Organic Rankine Cycle (ORC) unit integrated, to increase electric efficiency by recovering waste heat.

8.2.2 Operational experience

The fuel is normal wood fuel chips with 40% moisture wood chips with *in situ* drying of in the storage silo with air from a compressor. The price is 150 Euro/MWh. There were no reports on any specific problems related to fuel receiving or handling or feeding. No dusting, no self-ignition, no vapour forming or microbiology degradation.

There has been some bed agglomeration in the post-combustion chamber. There has been earlier occurrence of blocking in heat exchangers. The solution was to rebuild including a redesign of the coolers that made them more available for cleaning when needed. There have not been any ash problems and there is no ash recirculation.

The fuel feeder has been replaced and the screw conveyor was shown. The screw has been attacked by possible corrosion and erosion with fouling near the feeding point as can be seen in below photo, whereas the remaining part is shining like new. The problem is thus isolated to the last screw and can be controlled with efficient cooling.

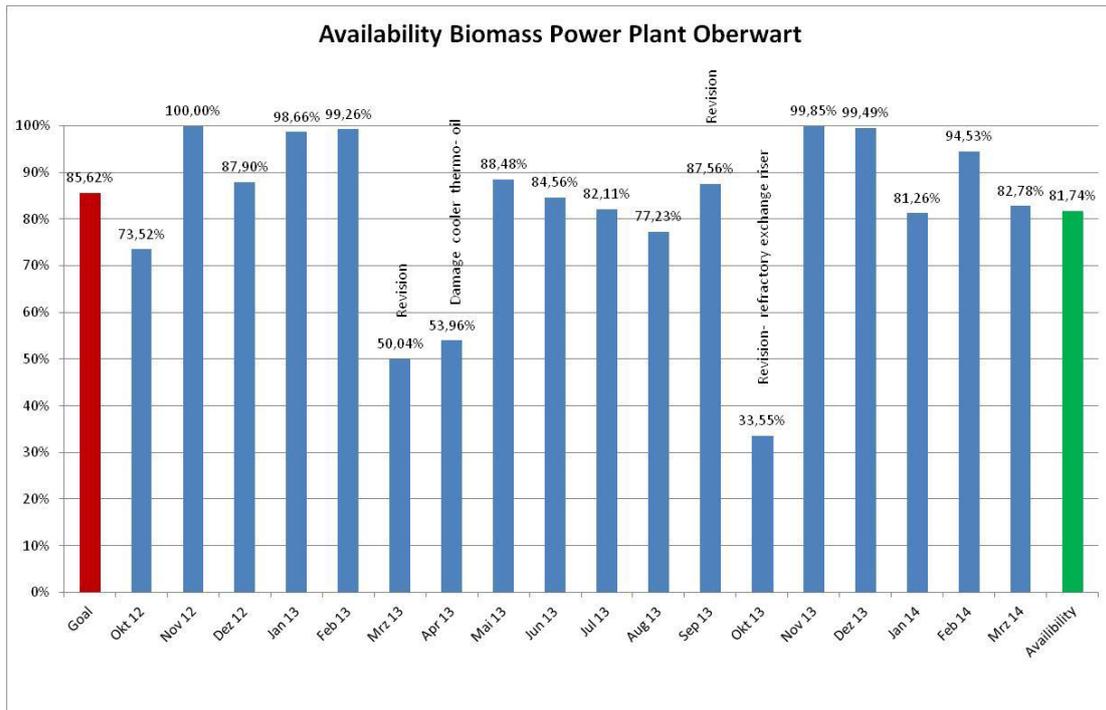


Figur 49. Foto av den utbytta skruvtransportören vid Oberwart. Flagnig, korrosion samt erosion kan ses på metallen med visst påslag.

Figure 49. Photo of the replaced screw conveyor at Oberwart. Scaling and corrosion and some erosion can be seen of the metal with some fouling.

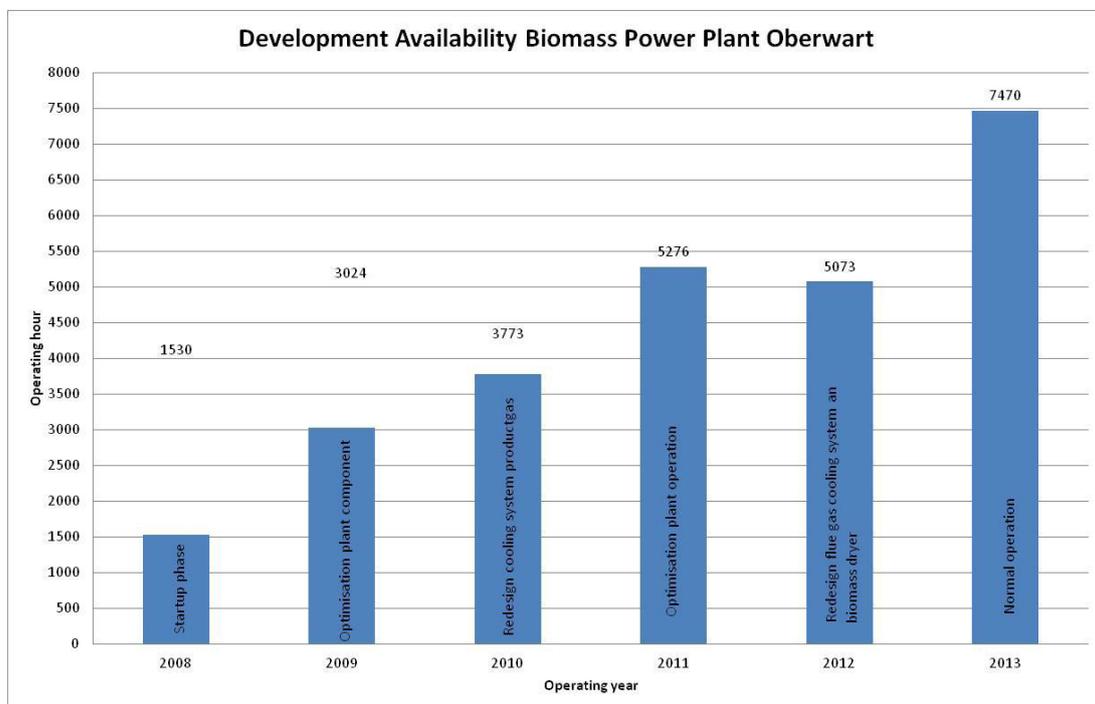
The gas filter operates at 150°C. A key to the tar cleaning is the scrubbing with RME. A part of the formed tar-slurry is fired in the combustion part of the gasifier system after separation from the main flow of used RME. The scrubber is saturated with ammonium carbonate, however, some ammonia is slipping through.

The plant is operated by one operator per shift. The availability can be seen in below diagrams. The value has been on average about 82% and sometimes up to 100% with a goal of 86%. It can be said that the first four years were troublesome and now the plant operates within target values.



Figur 50. Diagram av drifttillgänglighet vid Oberwart (Ref. Energie Burgenland).

Figure 50. Diagram of the plant availability at the Oberwart plant (Ref. Energie Burgenland).



Figur 51. Utveckling av drifttillgänglighet vid Oberwart (Ref. Energie Burgenland).

Figure 51. Plant availability development at the Oberwart plant (Ref. Energie Burgenland).

Regarding retrofit investments, process changes etc there was a major rebuild in 2012 (capital cost about €1-3 million), after gathering own operation experience. All known problems were tried to be solved. After new start-up and trimming very high availability could be achieved during 2013. Thus the whole optimization procedure from first start-up to acceptable availability took almost five years.

There were many reasons to the poor availability but one fact was that Repotec supplied the basic design but had very little contacts after that. The plant was built and run by the owner's team and Ortner. Thus, some problems early on can be contributed as lack of technology transfer from Repotec.

In conclusion, the startup problems can be significant even in the second plant if the technology transfer is not secured. In addition, the first plant at Güssing has not been rebuilt in a major way and do not have as high availability as the plant in Oberwart. The whole procedure took a very long time (several years) and the plant owner a local utility Energie Burgenland have taken most of the costs.

9 Repotec

9.1 Background

Repotec (Renewable Power Technologies Umwelttechnik GmbH) is a small technology company headquartered in Güssing, Austria. They have also a branch office in Vienna. The company objective is the design and erection of plants within the field of energy and environmental techniques, specialized on biomass power plants.

The small team of experienced specialists works in the field of power plants and plant engineering and construction. They have networking with the UNGER group which allows them the realisation of bigger projects.

9.2 Güssing

Much of the development work can be contributed to TU Wien (Vienna University of Technology) and Austrian Energy as the original developers and initiators of the technology and plant development. The first plant based on the FICFB technology in Güssing was built by Austrian Energy and Environment. As the company later faced economic problems Babcock Borsig took over. The team working with Güssing later formed Repotec as a separate company.

The process was thus developed during the 1990s at the Vienna University of Technology and resembled the SilvaGas process. The company was therefore founded in July 2001 to commercialise the gasification technology developed within the pilot plant constructed in Güssing. By Nov. 2001 the technology had been implemented and the plant started up in Güssing.



Figur 52. Foto av förgasningsanläggningen i Güssing.

Figure 52. Photograph of the gasification part Güssing plant.

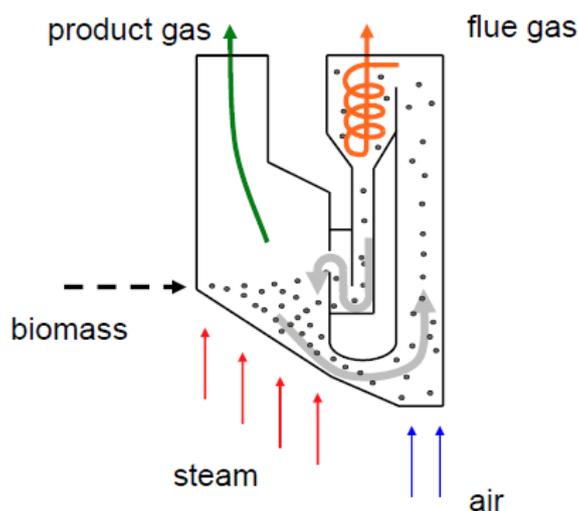
Plant fact sheet:

- Start of construction: September 2000
- Start up: January 2002
- Fuel 2.2 tonnes/h (wood chips)
- Water content: 15% (before drying 35%)
- Fuel input: 8 MWf
- Electrical power: 2 MWe
- Heat output: 4.5 MWth
- Electrical efficiency: 25% (net 20%)
- Total efficiency: 80%
- Owner and operator: Biomass Power Station Güssing Association.

9.2.1 Technology

The two-stage, combined fluidised bed gasifier and CFB combustion process (Fast Internal Circulating Fluidized Bed – FICFB) developed by the Technical University of Vienna (TUV), Austria, with Repotec has demonstrated exceptional rapidity of success in scaling-up the laboratory scale unit to a commercial demonstration plant. The principal novelty of the process is its ability to produce a medium calorific fuel gas without the use of oxygen.

The 8 MWf plant uses biomass that is fluidised in a bed with steam as oxidising agent for the gasification, or forced internal CFB. The resulting char is circulated with the bed material and further oxidised with air in a column, then cycloned and the heated sand is recycled back to the bed. See process below.



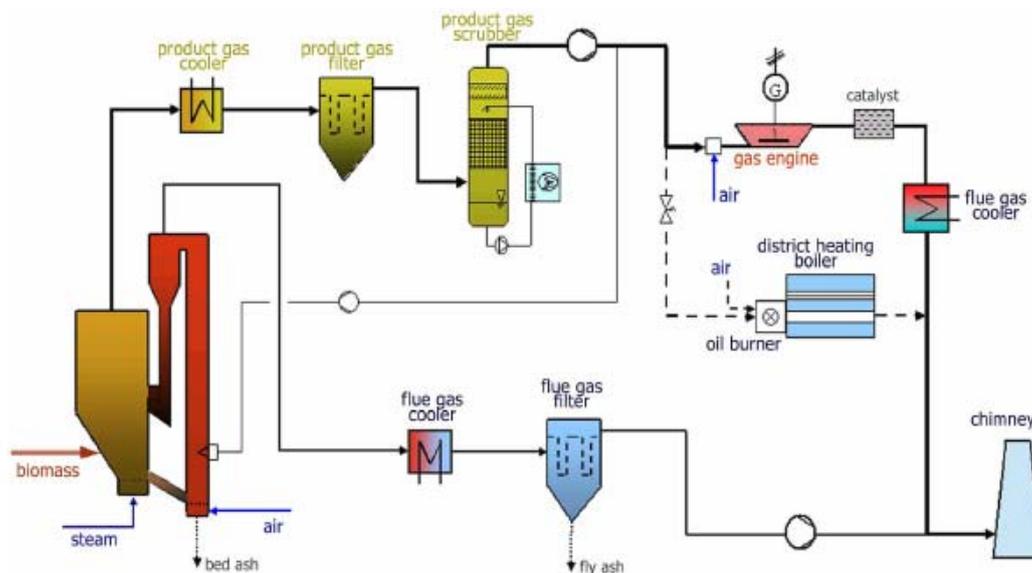
Figur 53. Schematisk bild över Repotecs förgasningsprincip med in-direkt värme- och ångreformerung i dubbelreaktorer (Ref. Repotec).

Figure 53. Schematic of the Repotec gasification principle with indirect heating and steam reforming in twin reactors (Ref. Repotec).

The basic idea of the FICFB concept is to divide the fluidised bed into two zones, a gasification zone and a combustion zone. Between these two zones a circulation loop of bed material is created but the gases should remain separated. The circulating bed material acts as heat carrier from the combustion to the gasification zone. The fuel is fed into the gasification zone and gasified with steam.

The gas produced in this zone is therefore nearly free of nitrogen. The bed material, together with some charcoal, circulates to the combustion zone. This zone is fluidised with air and the charcoal is burned. The exothermic reaction in the combustion zone provides the energy for the endothermic gasification with steam. With this concept it is possible to get a high-grade product gas without the use of pure oxygen.

The process is operated at atmospheric pressure at 850°C and employs a catalytically active circulating fluidised bed of solids that can reduce tar in the raw gases. The raw product gases are cooled for heat recovery and scrubbed with an RME to remove most of the tar. The condensate along with some of the scrubber solvent is recycled to the combustion zone for complete thermal decomposition of all condensable organic compounds produced during biomass gasification.



Figur 54. Processflödesdiagram av Güssinganläggningen (Ref. Repotec).

Figure 54. Process flow diagram of the Güssing plant (Ref. Repotec).

The gas composition has been given for the pilot operated at the Technical University in Vienna and the typical composition from the many hours operated at the Güssing plant.

Tabell 6. Gassammansättning från piloten och typiska värden från testserier (Ref. TUV).

Table 6. Gas composition from the pilot and typical data from several test series (Ref. TUV).

Compound	TUV pilot	Typical
Hydrogen	37.2% vol.	31.5% vol.
Carbon monoxide	25.2% vol.	22.7% vol.
Carbon dioxide	19.3% vol.	27.4% vol.
Methane	10.0% vol.	11.2% vol.
Higher hydrocarbons	3.0% vol.	4.0% vol.
Nitrogen	2.5% vol.	2.8% vol.
Water vapour	As dry	As dry
Hydrogen sulphide	100 ppmv	
Total	97.2%	99.5%

9.2.2 Operational experience

The fuel used is normal wood chips as well as round wood which are crushed. There were no reports on any specific problems related to fuel receiving or handling or feeding. No dusting, no self-ignition, no vapour forming or microbiology degradation.



Figur 55. Foto av bränslemottagningen och lagring vid Güssing.

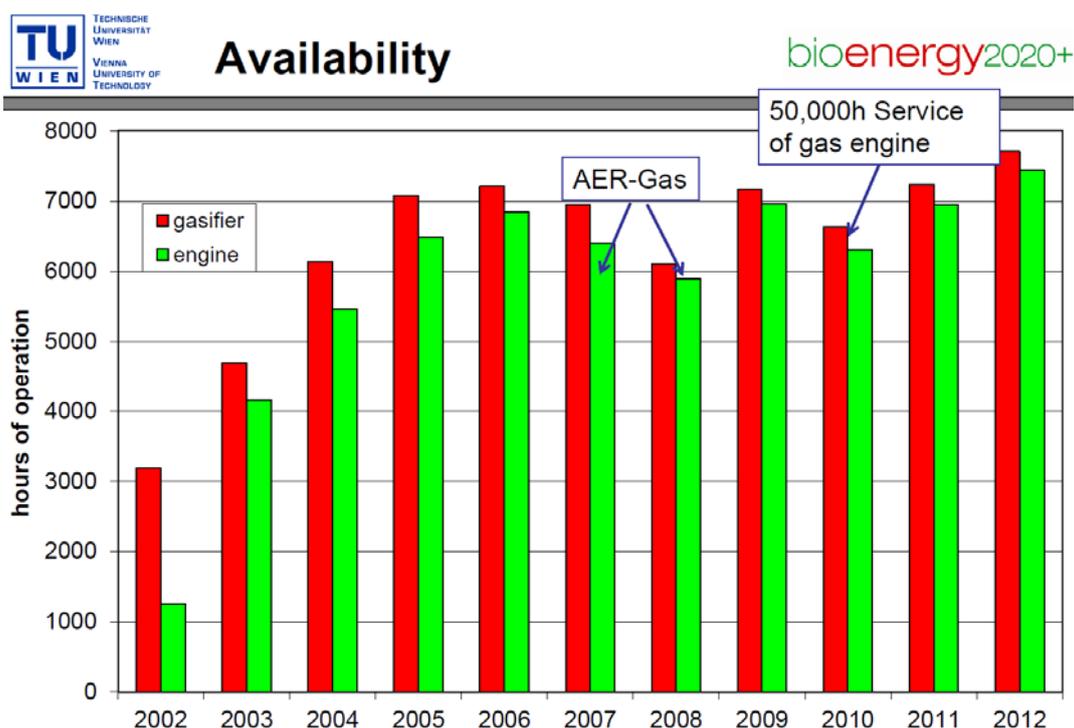
Figure 55. Photograph of the fuel reception and storage at the Güssing plant.

The biomass power plant launched its first power production in July 2002 with a Jenbacher engine and since been part of several research projects for novel tar removal by oil scrubbing, Fischer-Tropsch diesel synthesis in Sept 2005 and lately SNG production and fuel cell application with separated pure hydrogen.

The plant has operated successfully for a very long time and continues to be of high interest for further development. The current focus is continued development in different applications of the Güssing plant.

The basic application has been the JMS 620 GS GE-Jenbacher gas engine, which generates a gross ~2.0 MWe power and ~4.5 MW heat. The reported parasitic power consumption is ~0.2 MWe. The electrical efficiency of the Jenbacher gas engine is 36-37%. The net plant electric efficiency is 25% with an overall thermal efficiency of 80%. The reported cold gas efficiency² is 70%.

Until May 2006, the gasifier logged in more than 24 000 hours and the accumulated total operating time until today is >80 000 hours with the gasifier and about the same with the gas engine. Currently, the plant availability with gas engine operation is more than 87%. However, the plant is mostly operated on campaigns.



Figur 56. Diagram av drifttillgänglighet vid Güssing (Ref. TU Wien).

Figure 56. Diagram of the plant availability at the Güssing plant (Ref. TU Wien).

The gasification plant yields no liquid emissions (condensate) and ash only from the combustion zone (no carbon content). The tar content after gas cleaning is <math><50 \text{ mg/Nm}^3</math> and the gaseous emissions (ref. 5% oxygen, dry flue gas) are:

- CO <math><3000 \text{ mg/Nm}^3</math> (without catalyst)
<math><650 \text{ mg/Nm}^3</math> (with oxidation catalyst)
- NOx <math><500 \text{ mg/Nm}^3</math>
- Dust <math><20 \text{ mg/Nm}^3</math>.

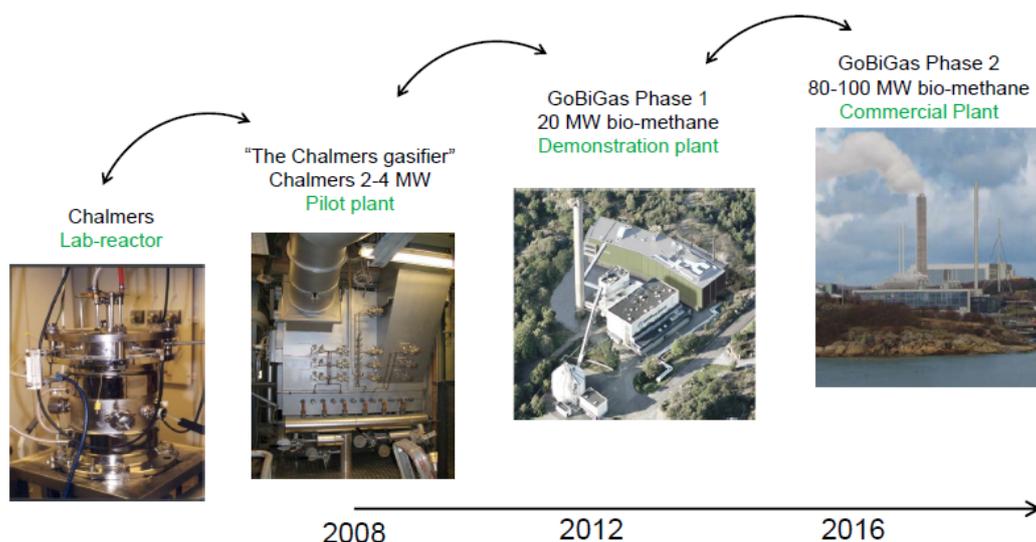
² The efficiency of a gasifier is generally expressed as Cold Gas Efficiency (CGE). CGE is defined as the chemical energy of the gas at room temperature divided by the chemical energy of the biomass input.

The biomass gasification and gas engine technology development and demonstration efforts continue to focus on resolving the issues related to tar contained in raw gases. Specifically, the gasifiers were developed with distinctly separate drying, devolatilisation, gasification, and combustion reaction zones and employing innovative thermal integration of these zones to produce a medium calorific value synthesis gas.

9.3 Gobigas I

Gothenburg Energy, which is owned by the city, has the mission to actively contribute to the sustainable development of the city of Göteborg. The company invests heavily in biogas and sees biogas (including biomethane) as one of tomorrow's most important energy carriers.

Gothenburg Biomass Gasification Project, GoBiGas, is Gothenburg Energy's largest investment in biomethane (or bio-SNG) production through gasification of solid biofuels and forestry wastes. The project has been split into two phases, a first demonstration phase of 20 MW product gas (32 MWf fuel input), to be followed by a second phase of 80-100 MW output of product gas. This technology and project development has been illustrated by Gothenburg Energy in below Figure.



Figur 57. Illustration av teknologitveckling till Gobigasprojektet (Ref. Göteborg Energi).

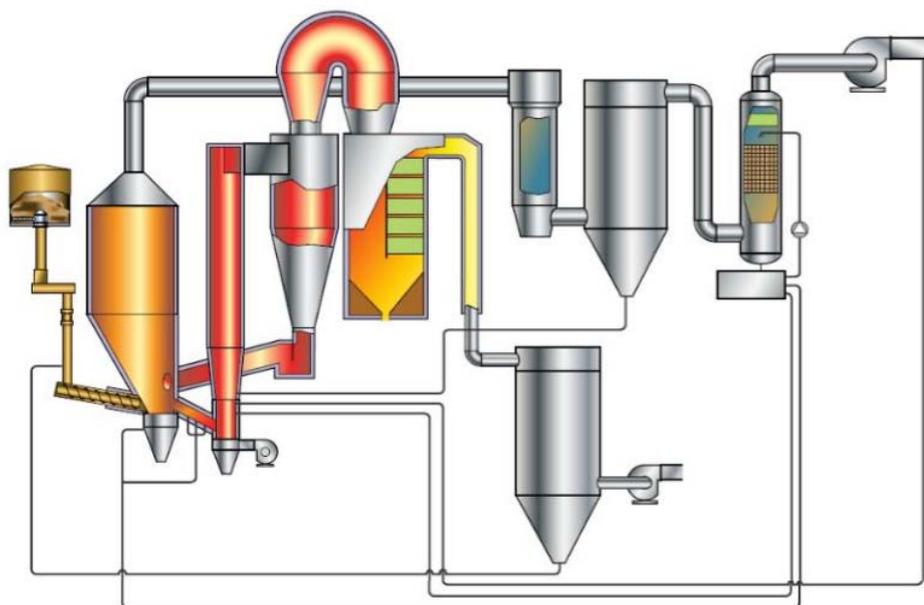
Figure 57. Illustration of the technology development for Gobigas (Ref. Göteborg Energi).

In spring 2006, Gothenburg Energy conducted a feasibility study which in 2007 was followed by more in-depth studies of various gasification technologies. The choice for the first phase was for indirect gasification with technology from the Austrian company Repotec. In 2008/2009, a basic design was carried out for the proposed technology for phase 1. Repotec licenced the technology to Valmet which was the gasification plant supplier. For the methanation technology, the CTU technology piloted in Güssing was evaluated, but the final choice fell on the technology of Haldor Topsøe.

The investment decision was taken in December 2010 and plant commissioning was expected in 2013. The estimated cost in 2008 was 825 million SEK, but at the time of the decision it had risen to 1075 million SEK where Jacobs Process won the EPCM contract. GoBiGas received a grant of 222 million SEK in 2009 from the Swedish Energy Agency. In late 2011, it was announced that the costs had risen to 1300 million SEK, and the last reported investment cost was some 1800 million SEK.

9.3.1 Technology

The solid biomass fuel is converted to a gaseous intermediate in the gasification plant (see section of Repotec for description). Note that Repotec licenced the technology to Valmet (then Metso) for the engineering, procurement and construction contract.



Figur 58. Schematisk bild över Gobigas förgasningsprocess (Ref. Göteborg Energi).

Figure 58. Schematic of the Gobigas gasification process (Ref. Göteborg Energi).

This so-called synthesis gas is purified and then upgraded in a methanation plant to bio-SNG or biomethane with a quality comparable to natural gas so that the two types of gases can be mixed in the gas network.

Through the choice of technology and plant design, the project aims to achieve as high efficiency as possible. The goals are to obtain 60-65% of the biomass as biomethane and an overall energy efficiency of above 90%. This includes, however, the use of electric heat pumps, and the import of electricity is not accounted for in the efficiency calculations, or the fact that a dry pellet fuel is used.

The phase 1 plant has been built in the western harbour area of Rya, adjacent to other energy installations of Gothenburg Energy including a biomass pellet-fired district heating boiler and the 220 MWe combined-cycle CHP plant. The planned location of phase 2 is a nearby plot with possibilities for both ship and rail supply of fuel.



Figur 59. Foto av Ryaverket med visade Gobigas anläggningar (Ref. Göteborg Energi).

Figure 59. Photo of the Rya location with the Gobigas plants showed (Ref. Göteborg Energi).

The plant location is conveniently located adjacent to the existing Rya CHP plant for easy access to the natural gas grid and the district heating network. However, the location is limited for a large-scale plant because of the fuel logistics. Still, the waterways can be used and fuel transported by boat to a harbour.



Figur 60. Foto av Gobigas anläggningen före första driftstart av förgasaren (okt 2013).

Figure 60. Photo of the Gobigas plant before first startup of gasifier (Oct 2013).

The flare is built on top of the building. Note that all process units are housed (not necessarily needed). Heat & power plants are custom to be housed but the petrochemical industry are custom to open process areas and most often not enclosed process units.



Figur 61. Foto av silo för träpellets till Gobigas.

Figure 61. Photo of the wood pellets silo to the Gobigas plant.

The plant is designed for several fuels including wood chips but will operate at start with wood pellets. The switch will be made when stable operation has commenced. This will lower the operating costs. However, there is a small area for fuel receiving and storage as well as the fuel logistics are troublesome if not the harbour can be used in the future with the larger plant in phase 2.



Figur 62. Foto av metaniseringsdelen av Gobigas.

Figure 62. Photo of the methanation part of the Gobigas plant.

The building permit did not allow a larger building housing, therefore the unit was placed on the sides of the building. There are also rock walls on the sides which made it difficult for the building to be extended. Note that there are no side walls to the unit.

9.3.2 Operational experience

The plant was mechanically complete in Dec. 2013 with first gasification in Nov. 13, 2013. The plant was reported to produce gas to grid in Q4 2013 but was delayed due to a number of problems. The operations can be divided into phase 1 and phase 2.

Phase 1

The operation between Nov. 2013 and April 2014 gave about 200 hours of operation. There were the following problems:

- Gas leakages,
- Cleaning of product gas coolers,
- Refractory repair (in Dec. and another in Feb.) because of wrong installation of the company,
- Malfunction of the RME scrubber due to wrong installation,
- Pressure fluctuations,
- Reprogramming of sequences (fuel, ash, etc),
- and more...

Phase 2

There has been established that there was a mechanical problem with the brick-lining refractory, and not a chemical one. The work onwards from April included how to reduce tar amounts as the tar molecular weight was heavier than expected which caused clogging in filters and the heat exchangers. A task force has been setup to tackle this.

Other activities have been recirculating coarse ash and adding some alkali in the gasifier which has given higher hydrogen share in the gas composition as well as lower carbon monoxide and less methane. There have since not been a problem with the gas coolers. They have only cleaned the cooler once or twice since April.

Sometimes the feeding screws have stuck. Therefore, the feeding is a new focus area. The lock-hopper system has been found to have valves which are not tight after a while and a backflow of product gas. There has been a change of the screw and better cooling although this is not finalized a solution for this.

The gas compressor which is the single most costly item and largest electricity consumer has been also the worst experience according to Göteborg Energi. Initially the gas torch showed a yellow flame indicating lots of tars in the gas. This has however changed and the torch flame shows a small tint of blue but almost visibly clear indicating good gas quality.

The project status as of October 2014 is the following. The organization for operation and maintenance is in place since one year. Start-up of gasification is on-going. All utilities have been tested and are in operation. A total of 1200 hours of gasification have been completed. The methanation part is ready for start-up with a schedule of gas to grid during 20 October for three weeks of operation. (However, the final day where biomethane gas was delivered to the grid was on 15 December, making it the first plant in the world to gasify biomass and inject into the gas grid).

The evaluation of GoBiGas Phase 1 will be held during 7 years – until 2020. Only when the plant has been operating to acceptance criteria will an investment decision be taken for phase 2. There is ongoing cooperation between Göteborg Energi AB / GoBiGas and the main suppliers.

The current purpose is to learn from the demonstration plant to enable scaling up to 100 MW in phase 2. The grant award from EU has been extended to 2020. The evaluation will include the following parameters:

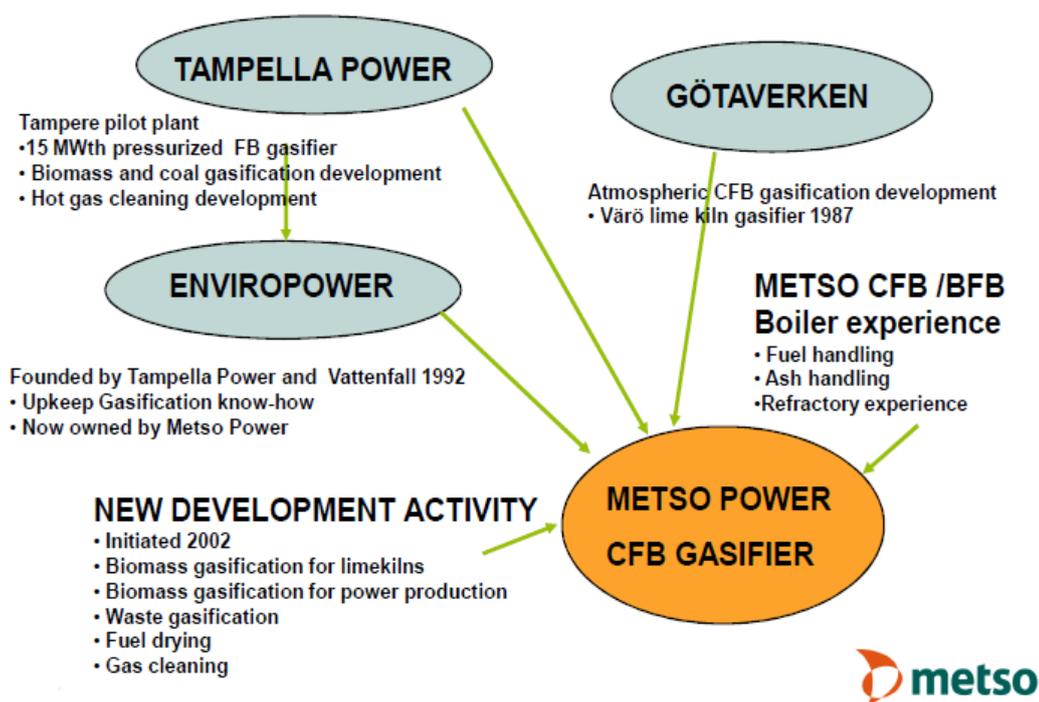
- Product quality
- Plant performance – efficiency etc.
- Plant availability
- Environmental footprint
- Maintenance needs
- Operating costs.

10 Valmet

10.1 Background

Valmet Corporation is a leading global developer and supplier of services and technologies for the pulp, paper and energy industries. They have about 11 000 professionals around the world. The company has over 200 years of industrial history and was reborn through the demerger of the pulp, paper and power businesses from Metso Group in December 2013. The gasification technology in Valmet thus was held in Metso before the demerger, whereas the new Metso serve the industries in mining, construction and oil and gas.

Valmet has developed a CFB gasifier which has been proven for a wide range of fuels from peat and biofuels to different waste fractions. It has been used for applications like to substitute oil, natural gas or other fossil fuels in industrial furnaces like limekilns, or to substitute coal, peat or other fossil fuels in power boilers. The size range for their gasifiers is 20-150 MWf.



Figur 63. Historisk förgasningsutveckling, nu ägd av Valmet.

Figure 63. Historic gasification development, now owned by Valmet (Ref. Valmet).

Valmet currently develops gasification projects for the atmospheric gasifier reactor which they have long experience with.

10.2 Värö

Valmet (Götaverken at the time) installed a CFB gasifier at Södra Cell's Värö paper mill, Sweden in 1987. The plant was fuelled by 30 MWf of bark and wood wastes, with the product gas used for co-firing in a limekiln. Enriched-air tests were conducted in 2003, in order to increase the capacity.

The gasifier is unique as Kvaerner who acquired Götaverken never built any further plants due to low oil prices. The gasification business belonged to the pulping and power division which was then sold to Metso Corporation (now Valmet).

Södra Cell has operated the plant in commercial operation for more than 25 years. In the year 2014 Valmet did contract with APP to supply 2x110 MWf gasifiers for lime kilns into the new Oki pulp mill now under construction.



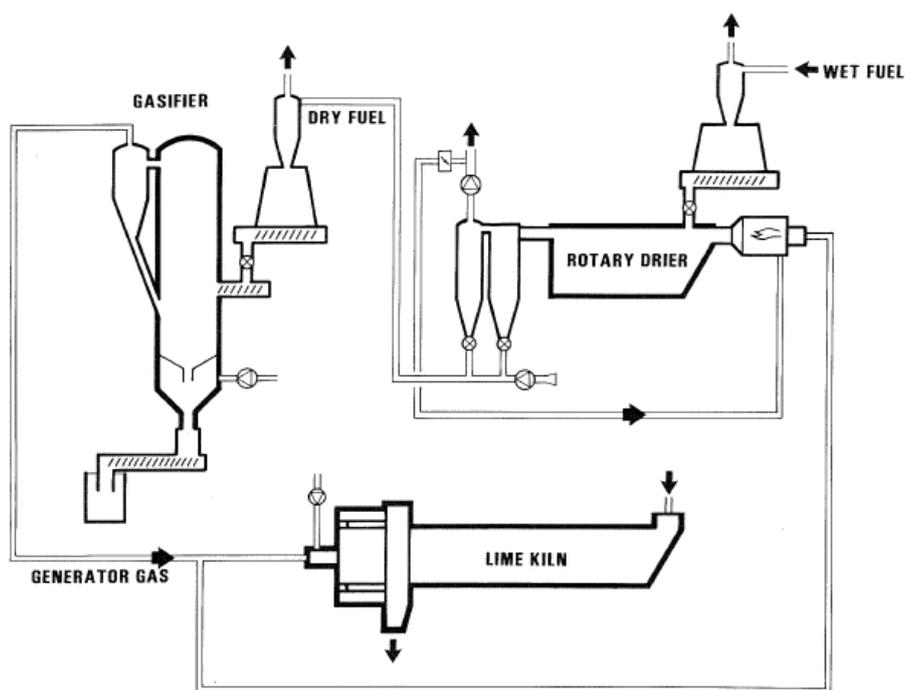
Figur 64. Foto av förgasaren vid Värö bruk, ägd av Södra Cell (Ref. Valmet)

Figure 64. Photo of the gasifier at the Värö mill plant owned by Södra Cell (Ref. Valmet).

10.2.1 Technology

The gasifier was used for lime kiln applications and both gasifier and lime kiln were operating at constant load. The lime kiln has been operated with produced gas from the gasification.

The gasifier is a Circulating Fluidized Bed (CFB) operating at 800 to 850°C. In the reactor there is a bottom bed consisting of bed material and ash from fuel. This bed is fluidized by air that is fed in through air nozzles in the reactor grid. Before entering the wind box, the air is pre-heated to 250°C in the air/product gas heat exchanger. The product gas is cooled to about 700°C.



Figur 65. Schematisk bild av processen vid Värö, ähd av Södra Cell (Ref. Valmet).

Figure 65. Schematic of the process at the Värö mill plant owned by Södra Cell (Ref. Valmet).

Crushing of the fuel, both bark and wood wastes, takes place in a primary and a secondary hammer mill to prepare the right fuel size for the gasifier. The feed system consists of two pressurized rotary feeders with cooled transport screws to the gasifier. The fuel feed placed a few meters above the bottom of the bed to create two distinct reaction zones. In an upper zone, the fuel reacts via flash pyrolysis in the hot bed / inert flue gas atmosphere to a gas rich in C_2 :s and also tar.

The lower reaction zone is essentially for char combustion (recycled char) and, to some extent, char gasification. In theory, char combustion / flash pyrolysis should be balanced if the fuel has a small particle size. In practice, and with coarser particles, the zones will be less well defined and separated. To limit the amount of heavy hydrocarbons in the gas and to allow for carryover of bed material to the lime kiln, dolomite is used as gasifier bed material.

The gasifier is a refractory-lined free-standing vessel with solids recycling and air/gas heat exchange. The product gas is controlled by valves and piped to the dryer furnace and the lime kiln.

10.2.2 Operational experience

The Värö plant was commissioned in 1987 by Götaverken. The gasifier is an atmospheric circulating fluidised bed gasifier with 30 MWf of fuel capacity. It is one of few commercial units that have been in operation for that long period of time.

Due to a conservative design of the heat exchangers and pipes (i.e. low velocities), a tendency for char/tar adhesion to the surfaces and settling of dust in the lower region of the horizontal pipes occurred. This led to mechanical problems when restarting the unit (i.e. differential expansion). After a few years, a smaller transport pipe was installed which solved the problem.

Severe erosion/corrosion of high temperature control valves also occurred and led to a reduction of the number of delivery points for the gas from three to two. Stopping the fuel feed and burning off the deposits every week or second week cleaned the heat exchangers sufficiently. With improved operational procedures the need for cleaning was eliminated.

A single hot gas cyclone is an inefficient dust cleaning device when applied to a “dust generator” such as a CFB. The high dust content was still a problem and was not completely solved despite many years of operation.

During operation of the plant over a period of more than ten years most of the initial problems were solved. Due to the low oil price to industry (as it is not subject to environmental tax), the owners of the plant are not interested in extending the plant as no substantial additional investment can be justified.

Even though the plant has been in routine commercial use some development tasks has completed at the site. In 2003, the Värö gasifier was operated with enriched-air to increase the capacity of the plant. Valmet installed a slipstream gas cleaning test rig at the site in 2008, which is actually a part of R&D towards waste gasification and not part of Värö operation. The gasifier became a source of information and was the test bed in 2009 for testing of high temperature filtration.

The Värö gasifer was stopped in April 2014 because of a new mill investment program and where the new limekiln is now fired by wood pellets.

10.3 Lahti – Kymenjärvi II

The Kymijärvi II plant located in Lahti, Finland, about 100 kilometers north of Helsinki, is the world’s first gasification power plant that runs purely on SRF³. The plant was officially inaugurated on 8 May, 2012. See Figure below for a photo.

³ SRF = Solid Recovered Fuel. Solid fuel prepared from non hazardous waste to be utilised for energy recovery in incineration and co-incineration plants and meeting the classification and specification requirements laid down in EN15359 (Standard from the European Standardisation Committee).



Figur 66. Foto av Lahti kraftvärmeverk med 160 MWf bränsle förgasare med SRF (Ref. Valmet).

Figure 66. Photo of the Lahti power plant with 160 MWf of SRF gasification (Ref. Valmet).

The test runs started in January 2012, and the plant reached full heat and electricity capacity. It produces 50 MWe of electricity for the national grid and 90 MW of district heat for the city of Lahti and its neighboring areas. The plant effectively replaces the adjoining older, mainly coal-fired Kymijärvi I power plant.

10.3.1 Technology

The fuel at the power plant consists of various types of industrial, commercial and building site waste. Some household waste is also used. Combustible waste turns into SRF through a sorting process that takes place by subcontractors from whom Lahti Energy purchases it. This differentiates a gasification plant from a waste incineration plant that charges for the waste that it combusts.

The SRF is converted into a raw gas with CFB technology supplied by Valmet, then cooled and cleaned. This clean product gas is fed into a boiler to produce steam for the steam turbine. This is also the largest SRF gasification plant in the world. The efficiency ratio at the new plant is high; up to 87% of the fuel energy can be turned into electricity and heat.

Metso delivered the circulating CFB gasification process, gas cleaning and cooling, the steam boiler and the environmental protection system, and the extensive automation system for the entire plant.

10.3.2 Operational experience

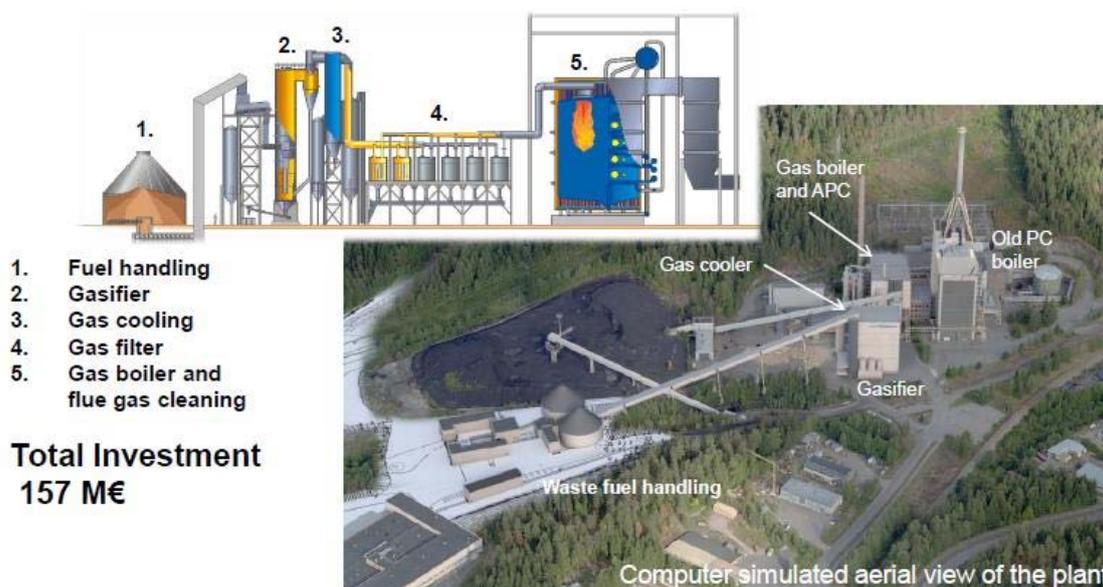
Valmet has installed an industrial scale solid waste gasification demonstration plant in Lahti with 2x80 MWf for commercial operation in April 2012.

The Kymijärvi II plant has steam parameters of 540°C /120 bar which are extreme for any waste firing unit and results in high yield of electricity – this has proved to work without risk of corrosion. The plant has been in commercial operation for more than 17 000 hours.

The initial startup was reported to function well. However, there were initial problems with the availability, with foremost the filter but now with improved operational procedures the situation has improved to satisfactory level. A number of the textiles in the baghouse filters have broken.

There have been changes to overcome these problems, mainly in the routines for start and stop. In addition, there are increased possibilities for section operation to be able to operate with fewer filters.

There have not been any corrosion damages, and it seems that HCl is released together with the flue gases and does not add to heat exchanger surfaces. The reason being that alkali is caught in the filter and therefore does not react with HCl to pose a risk for corrosion on surfaces. In conclusion, no corrosion in the boiler or heat exchangers has been found.



Figur 67. Foto av Lahti kraftvärmeverk med schematisk layout av förgasaren och bränslehantering (Ref. Valmet).

Figure 67. Photo of the Lahti power plant with schematic layout of the gasifier and fuel handling (Ref. Valmet).

SRF is a challenging fuel due to its variable nature. Correct information about it is of utmost importance in running the gasification process and the CHP production efficiently. The importance of fuel reception is shown by the fact it has its own control room.



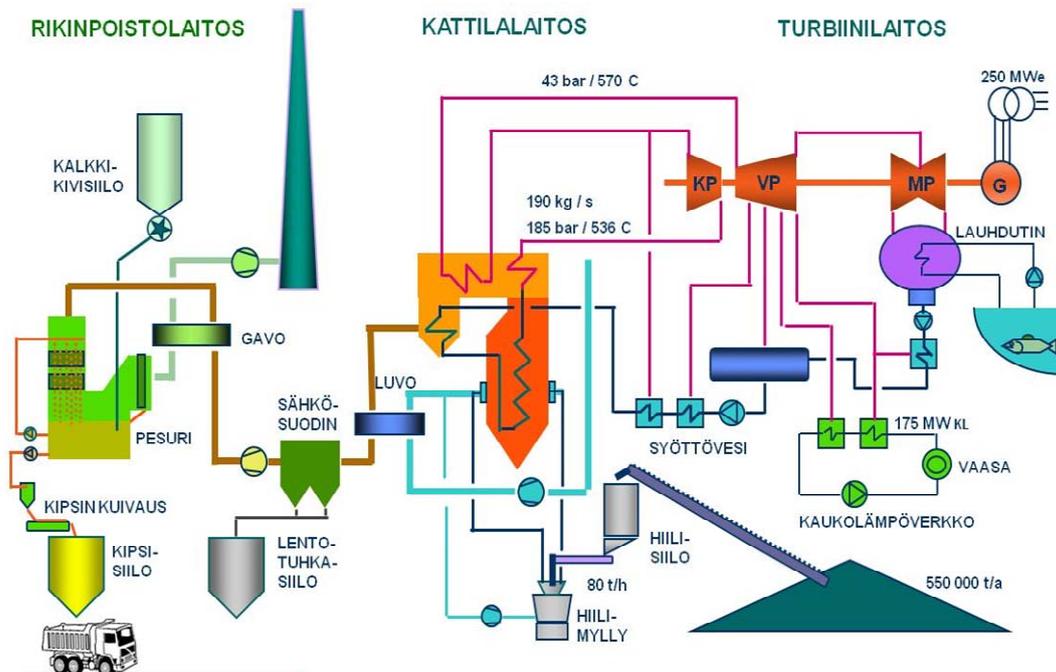
Figur 68. Foto av avlastning av SRF vid Lahti-verket (Ref. Valmet)..

Figure 68. Photo of unloading of SRF at the Lahti power plant (Ref. Valmet).

All the collected information is stored in the plant database and used for planning the operations, following up financial matters and connecting to laboratory analyses. This results in more increased plant efficiency. For example, knowing the moisture level or weight of each load makes it possible to predict each load's energy content and thus optimize fuel acquisition.

10.4 Vaasa

The Vaskiluoto Power Plant is located on an island just outside of Vaasa, Finland and is equally owned by EPV Energy AB and Pohjolan Voima Oy. The existing CHP plant, which provides base-load power, consists of a 560 MW Benson Boiler 185 bar/536°C built 1982. The electrical output is 230 MWe and 175 MW of heat. The fuel is pulverized coal and the consumption at full load with coal alone is 80 t/h and 550 000 t/a.



Figur 69. Schematisk bild över kraftvärmeverket i Vaasa, inte inkluderande förgasningen (Ref. Vaskiluodon Voima Oy).

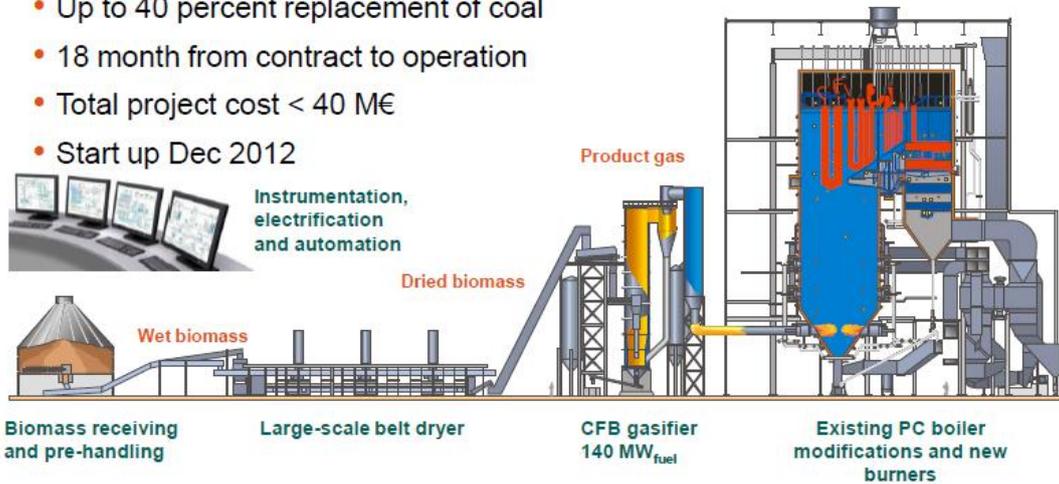
Figure 69. Schematic of the CHP plant in Vaasa, not including the gasification (Ref. Vaskiluodon Voima Oy).

The facility has previously been in operation throughout the year in addition to a maintenance shutdown at one month during the summer. Recently, a waste-burning plant has started in Vaasa. It will continue to go as base-load why operation uptime of this Vaskiluoto plant will be shorter, about nine months per year as the city of Vaasa is relatively small and current electricity prices are also relatively low.

10.4.1 Technology

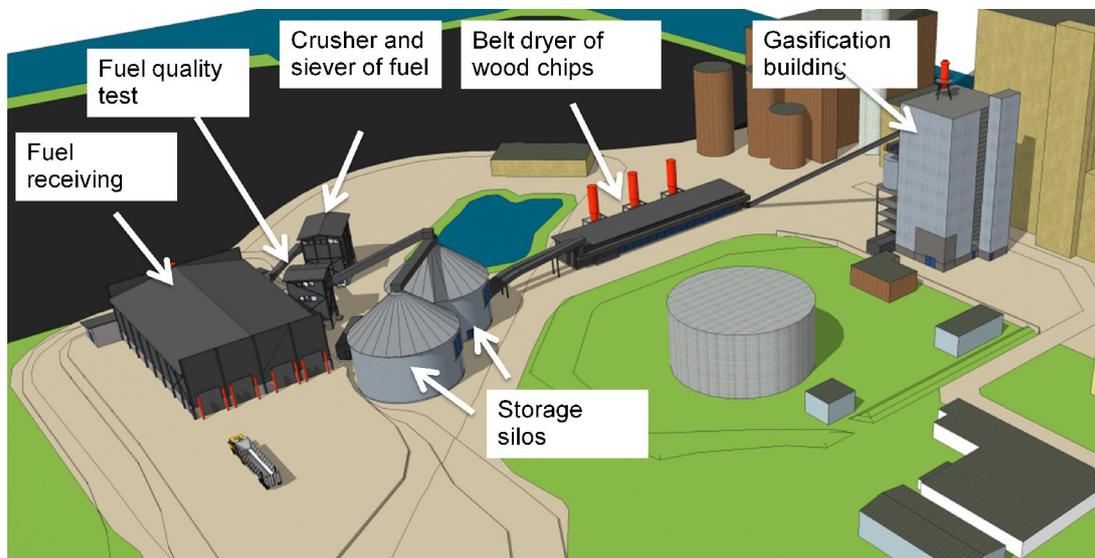
The gasification plant supplied by Valmet was commissioned in October 2012 and the fuel capacity is 140 MWf. It is a pre-step to the existing coal fired boiler. The gasification plant can replace up to 25% of the coal at maximum load. 40% annual basis as the plant will not be at full load all the time.

- 140 MW biomass gasifier and dryer
- Adjoined to the existing 560 MW coal-fired power plant
- Up to 40 percent replacement of coal
- 18 month from contract to operation
- Total project cost < 40 M€
- Start up Dec 2012

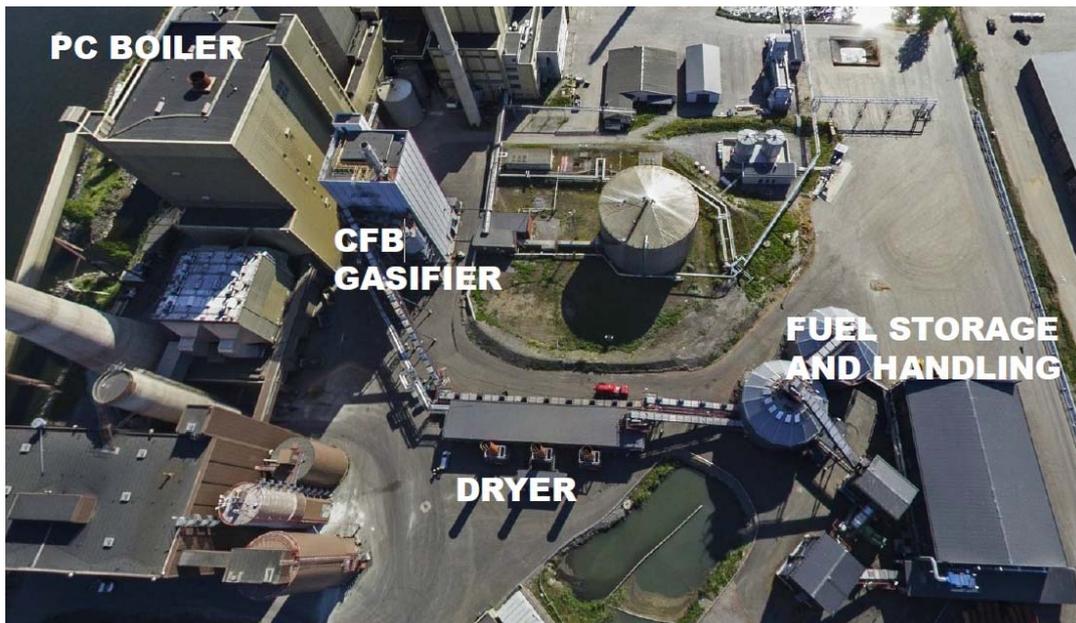


Figur 70. Schematisk bild av Valmets CFB förgasningsanläggning i Vaasa (Ref. Valmet).
 Figure 70. Schematic of the Valmet CFB gasification plant in Vaasa (Ref. Valmet).

To date, the operating time has been about 9000 hours (with 5000 hours the first short season) and availability has been reported high, 97% in the first year of operation.



Figur 71. Schematisk bild av förgasning i Vaasa (Ref. Vaskiluodon Voima Oy).
 Figure 71. Schematic of the gasification plant in Vaasa (Ref. Vaskiluodon Voima Oy).



Figur 72. Flygfoto av förgasningsanläggningen i Vasa (Ref. Valmet).

Figure 72. Aerial photo of the gasification plant in Vaasa (Ref. Valmet).

140 MWf is large for an atmospheric gasifier but Valmet has engineered drawings for a similar gasifier of 300 MWf. The investment cost for the gasification plant including some fuel terminals etc was €40 million. Support was obtained from the Finnish Ministry of Employment and the Economy with €10.8 million.

In addition, Valmet has just received an order for two similar gasifiers of 2x110 MWf to a pulp mill in Indonesia. The fuel will be Eucalyptus and acacia and produce gas for a limekiln, like the case was for Värö.



Figur 73. Foto av förgasningsanläggningen i Vaasa, maj 2014.

Figure 73. Photo of the gasification plant in Vaasa in May 2014.

The fuel for the gasification plant in Vaasa consists of 80-90% of wood chips and 10-20% of energy peat. The quality demand on the chips is the same as for a conventional CFB boiler. The addition of peat is sometimes larger, especially in cold weather, as there may be ice in the biofuel. The admixture of peat has at times been up to 40%.

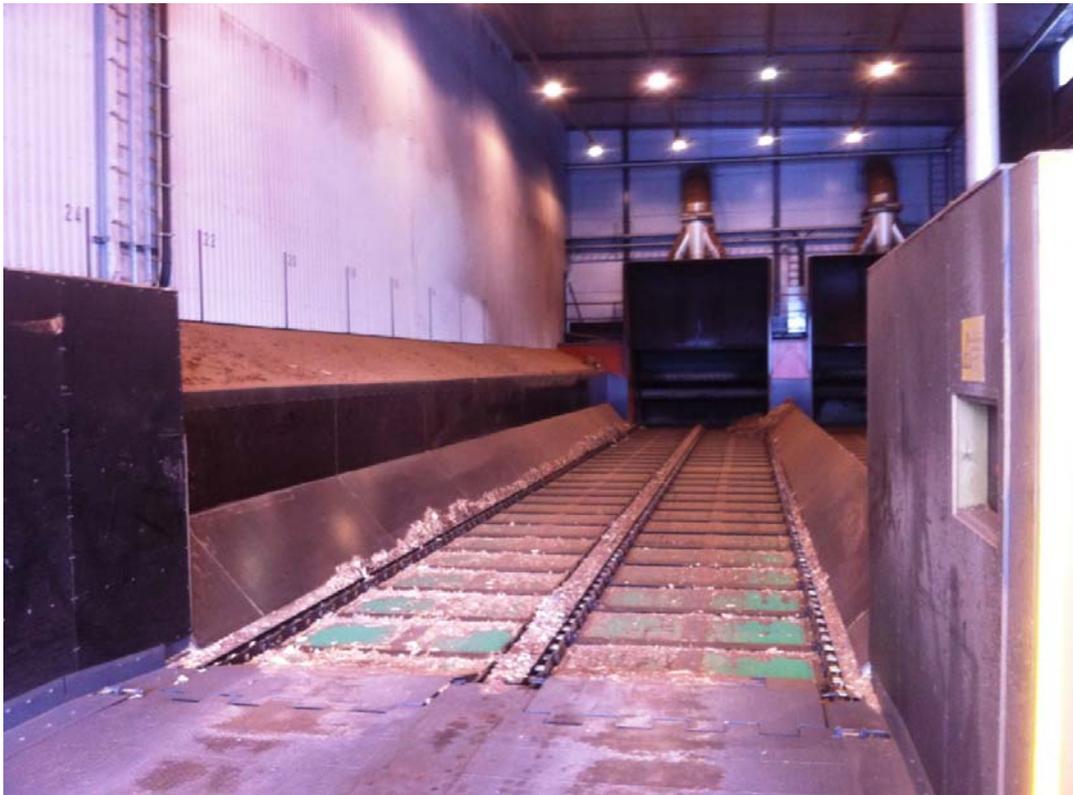
There are also some stumps in the chips and these may cause problems in the plant because of the possibility to contain large stones. Still, there have not been any problems even though these fuels are used in daily use.

At the fuel reception, four cars unloaded simultaneously. Peat and wood chips are unloaded at the same place but in different bands (conveyors) and mixed only after the belt-dryer. After receiving, the fuel goes first to the metal separation, crushing and screening. Delivery inspection is conducted wherein the moisture content of the wood chips is determined. Seven to eight fuel samples are taken from each car. Intermediate storage is done in two 2500 m³ silos.



Figur 74. Foto av bränslemottagningen i Vasa, maj 2014.

Figure 74. Photo of the fuel receiving plant in Vaasa in May 2014.



Figur 75. Foto av bränslemottagningen i Vasa, maj 2014.

Figure 75. Photo of the fuel receiving plant in Vaasa in May 2014.

Drying of wood chips takes place in a heat-driven (73-90°C) belt-dryer. The heat demand varies with the moisture content of the fuel and the outdoor temperature and is between 8-17 MWf in this facility. The dryer capacity is therefore expressed as maximum evaporation and is 10 t/h of water. The fuel flow at the maximum load is between 150-180 m³/h depending on the moisture content.

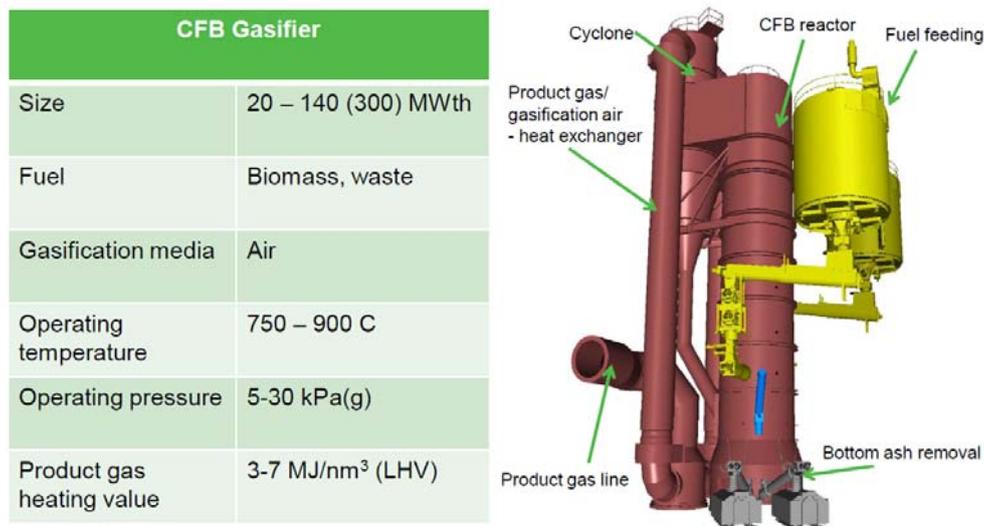
The belt dryer is space-consuming, about 51 m long and 8 m wide and with a height of 8 m. It is equipped with three fans and exhaust. The moist air leaving the dryer is reported to have a temperature of about 18°C. Problems with smell do not exist as the temperature is low.



Figur 76. Foto på bränsletransportören till torken och förgasaren och byggnaden till höger (ljusgrå) i Vasa, maj 2014.

Figure 76. Photo of the fuel conveyor to the dryer and the gasifier building to the right (light grey) in Vaasa in May 2014.

The gasification temperature is 850°C, where the top part of the reactor has a temperature of about 900°C. The gasifier is ceramic-lined and is standing apart from hanging reactors. The height is 33 m and the inner diameter 5 m. The ceramic lining is 2 dm thick and comprises two layers, one heat insulating and one wear layer. There are two fuel feeding points. The bed sand is silica sand. The gasifier is fitted with a startup oil burner that heats the reactor to 450°C. The ramp up speed is 50°C/h and takes about 12-13 hours from cold conditions to full load. The cooling of the gasifier reactor takes about same time. Hot start is very fast, in minutes.



Figur 77. Schematisk bild av Valmet CFB förgasare (Ref. Valmet).

Figure 77. Schematic of the Valmet CFB gasifier unit (Ref. Valmet).

After gasification, the gas is cooled down to 600-650°C in three parallel air pre-heaters, which then merges into a gas pipe that goes into the boiler and combustion. The ash is taken out in a closed compartment to two containers. There is no special treatment before it deposited.



Figur 78. Foto av gasröret från förgasningsreaktorn till pannan.

Figure 78. Photo of the gas pipe from the gasification reactor to the boiler.

The minimum load for stable operation is 70 MWf. With wetter fuel, the load could be taken down further. The gasifier is equipped with an external torch. It is sized to a reactor discharge which takes about 15 minutes. The torch is not contained but is built with a shell. Therefore, the flame is not visible from the surrounding area. Total inertization takes 30 minutes and is done by injecting steam into the gasifier.

When the gasifier was designed for its size, attention was given to the existing boiler for waste gas volumes, the risk of corrosion, etc. Therefore, additional rebuilding could be held down. In principle, the boiler is only retrofitted with gas burners. The old leaking air-preheater (termed LUVVO) has also been remodeled to reduce gas leakage but it was needed notwithstanding the gas burning. It is possible to burn gas and coal powder in the ratio of 50/50 which was showcased for two weeks during minimum load 70 MW gas + 70 MW carbon powder.

There are four new gas burners in the boiler, placed two by two in a zigzag pattern, opposite each other. The burners are of 35 MW each and have a diameter of more than 1.2 m. Both sulphur and nitrogen emissions have been reduced by co-combustion of gas, compared with 100% carbon powder.

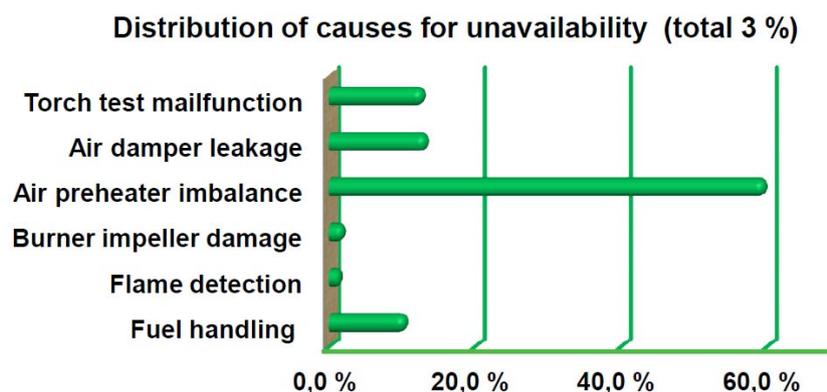
The plant has no accumulator, which means that the load of the facility is gradually lowered during the nights. The operating mode is maintained with full gas load and lower load on coal powder. The plant managers reported that after installing the gasification plant with the gas burners the performance of the boiler has increased. Amongst other things the heat distribution is better than before.

10.4.2 Operational experience

Since commissioning the gasification plant availability has been 97%. The largest loss of availability was due to a leak in the bellows to the gasifier air-preheater. Smaller problems have occurred in the fuel handling and conveyors but nothing major.

There were no reports on any specific problems related to fuel receiving or handling or feeding. No dusting, no self-ignition, no vapour forming or microbiology degradation.

For the season of 2013/2014 the plant was planned to run 600 GWh of biofuel but due to low coal and electricity prices production was lower, approximately 400 GWh. Still, the first operational year of 2013/2014 the availability was very high, 97% and the causes for unavailability are shown in below Figure.



Figur 79. Diagram av orsaker för sämre tillgänglighet första driftåret (Ref. Valmet).

Figure 79. Diagram of the causes for unavailability the first operational year (Ref. Valmet).

There have been only minor effects on PC-boiler operation, no boiler trips. The fuel unloading pockets were designed with high separating walls and some types of trucks have had difficulties to operate between those walls. In the fuel sampling system there has been jamming with wet and cold peat. Temperature differences on the body material of air heaters have caused distortion and damaged bellows of the gas ducts.

There have been no instabilities in the boiler evaporator. NO_x-emission levels have been under the limits of the environmental permit (500 mg/Nm³). After the modification the emission level has been around 350 mg/Nm³ and about 400 mg/Nm³ last year. The dryer has functioned fine. The potential risk of the hot corrosion of the superheaters was noticed and therefore a theoretical study was made by Valmet. As a result it was decided to keep the rate of biofuel always under the rate of coal. For the moment Vaskiluodon Voima and Valmet are studying the possibility to substitute coal 100% with gasified biomass.

The nearest accommodation housing is approximately 300 m from the plant. There have not been any disturbances reported from neighbours.

11 Additional plants

This chapter details plants with supplier companies which are either not currently active in biomass gasification or have become bankrupt and stopped operations. The reference plants however are interesting and relevant for a broader understanding.

11.1 Envirotherm and AMER-9 plant

Envirotherm GmbH is headquartered in Essen, Germany and belongs to the US based Allied Resource Corp., Wayne, PE, USA. Envirotherm was founded in July 2003 and offers technologies, which were taken over in an asset deal from Lurgi Lentjes AG, Düsseldorf, Germany.

Envirotherm is an engineering company without manufacturing capacity. Their technological focus is in the fields of synthesis and fuel gas generation from solid feedstocks, also from secondary raw materials, of thermal disposal of waste and industrial slurries as well as hazardous wastes in solid, liquid, paste and gaseous form, as well as dedusting through electrostatic and bag filters. Filters on a ceramics basis are available for use in hot gas cleaning. The company is not active in pursuing gasification projects on commercial terms and conditions.

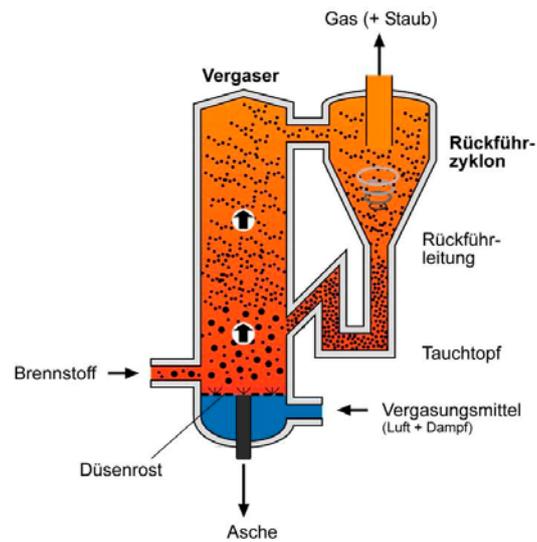
Among the plants being built was the 83 MWf CFB gasifier for RWE at the pulverised coal-fired AMER-9 power station, in The Netherlands. The plant uses demolition wood: qualities A and B with 150 000 tonnes per year and the gas is burnt in AMER-9 boiler replacing 80 000 tonnes of coal per year.

Another plant was the Rüdersdorfer Cement, Rüdersdorf (near Berlin), Germany, CFB gasification (100 MWf). Commercial operation started in 1996, for gasifying biomass but also other secondary raw materials from various sources. Availability was reported as over 90%, however the status is not clear. This plant was integrated in a cement factory and supplied up to 40% of the energy demand of the cement process. Produced ash was used as raw material for the cement process.

11.1.1 Technology

The process is based on the Envirotherm (Lurgi CFB) atmospheric air-blown circulating fluidised-bed gasifier operating at about 800°C and 140 kPa. The product gas is cooled in two stages with first step from 800 to 600°C while the gasification air is preheated to 500°C.

The product gas is cooled in the second stage to 240°C in the waste heat boiler for steam production. The char and particulates are removed by passing syngas through a cyclone and a bag filter. The gas is washed in a wet-scrubber and cooled to 45°C.



Figur 80. Schematisk bild av Envirotherm (Lurgi) CFB-förgasare (Ref. Envirotherm).

Figure 80. Schematic of the Envirotherm (Lurgi) CFB gasifier (Ref. Envirotherm).

11.1.2 Operational experience

The 83 MWf CFB gasifier is operated by RWE Essent and is located at the pulverised coal-fired AMER-9 power station, in The Netherlands.



Figur 81. AMER-9 anläggningen i Geertruidenberg, Nederländerna (Ref. RWE Essent).

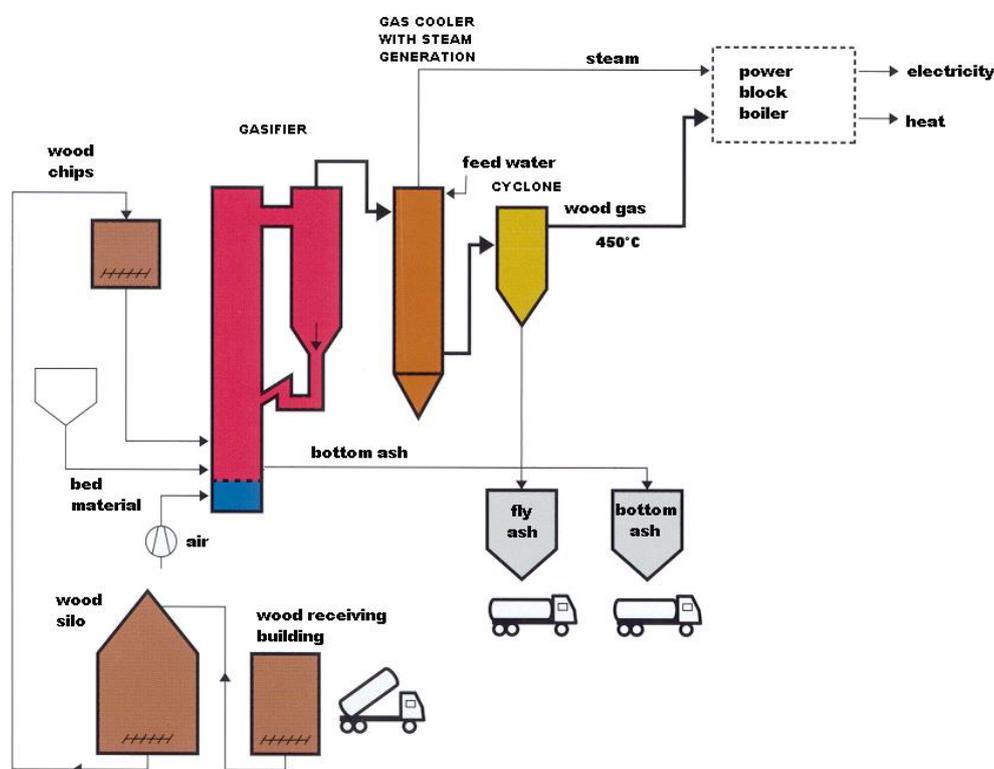
Figure 81. The AMER-9 plant in Geertruidenberg, The Netherlands (Ref. RWE Essent).

The development and commercialization of the technology could be described as that three project phases were necessary instead of one:

1. Contracting, construction, commissioning (two years)
2. Substantial modifications and long commissioning periods (three years)
3. Re-design by RWE Essent, construction and commissioning (almost two years)

The plant started commissioning in 2001 but due to problems the operating hours were limited. In 2002, the plant was rebuilt with the gas cooler changed, filter and scrubber removed with a re-commissioning late 2002 and guarantee tests early 2003.

Essent then took over the operation and Lurgi became not longer in charge of the project. A restart was reported in July 2004 with 1500 h operation time since reconstruction 2002. The plant has now accumulated about 30 000 operating hours.



Figur 82. Förgasarens processschema efter projektfas 2 (Ref. RWE Essent).

Figure 82. Gasifier process scheme after project phase 2 (Ref. RWE Essent).

Project phase 1

The original process concept (project phase1) included fuel logistics with the fuel delivered by truck. A circulating fluidized bed gasifier with sand as bed material. Gas cooling down to 220°C by generating steam (water/steam pipe gas cooler). Fly-ash removal by bag filters. Wet scrubbing is applied to remove ammonia. Gas at 95°C is cofired in the coal boiler.

Project phase 2

The second phase included substantial modifications and long commissioning periods with main issues including:

- Agglomeration tendency in gasifier
- Very fast gas cooler fouling
- Ignition of fly-ash in gas cooler during start-up
- Ignition and fire in bag filters during start-up
- Wear in the wet scrubbing section.

The results after project phase 2 were the following. The gas cooler was modified: the outlet temperature was raised to 450°C. The filters were replaced by cyclones. Wet scrubbing was removed (by-passed). The remaining problems were agglomeration tendency, moderate gas cooler fouling, and unavoidable ignition of fly-ash in gas cooler during start-up, too complex automation and safeguarding system

After project phase 2 the conclusions were the following. RWE cancelled the cooperation with the supplier and continued the modifications and commission by themselves. RWE Essent started own re-design with three main areas.

1. Metal-catcher in fuel supply (however, not successful in the end).
2. An important issue was to avoid agglomeration and these actions were taken:
 - Coarser sand
 - Start-up of the burner outside the gasifier
 - No more air-supply (for fluidization) to the swan-neck.
3. Oxygen-free operation under all circumstances:
 - Under-stoichiometric operation of start-up burner; no wood combustion anymore (as this occurred originally during start-up)
 - Fluidization with steam instead of air during start-up and cooling-down
 - Result: ignition of fly-ash in the system was definitely avoided!

Project phase 3

Project phase 3 continued with RWE Essent's redesign of the plant with further modification and commissioning. The automation concept was: Push button start-up in any condition; avoiding false starts (avoiding damaging temperature gradients). The safeguarding included: Focus on O₂ and temperature, O₂ < x% with x only dependent on the temperature; simple and clear.

The operational results included the following. The fuel used was shredded demolition wood ('B-wood') only. The start-up became smooth and assured. The simplified automation concept is effective. There is hardly any agglomeration problem now in the fluidized bed. There is no more blocking of the swan-neck. Metal parts in the fuel remain potential cause of trips (no redundant fuel feeding system).

Gas cooler fouling still requires regular off-line cleaning. The availability is limited to 5000 hours per year, mainly due to single fuel feeding system and off-line gas cooler cleaning necessity.

In 2014 the governmental support stopped as the ten years support contract with the government ended, and the plant company started looking for cheaper fuels. The fluidized-bed process can fundamentally accept a range of different fuels. RDF is at the moment an interesting option. Specifications of RDF fluff are rather comparable with those of B-wood. First tests with RDF mixed with B-wood started in 2013.

Testing gasification of RDF/B-wood mixture has given these initial test results. Logistics test was positive: RDF fluff transported well in screws, elevators, conveyor belts and silo; less dust than with B-wood; smell was very limited. A mixture of 25% RDF and 75% of B-wood tested gave very fast gas cooler fouling and blocking. The analysis showed that blocking was in the part with the highest gas temperature. The conclusion was that ashes from RDF gasification are sticky at temperatures above 780°C. The gasification temperature was 840°C (it was kept the same as with B-wood).

This followed with lowering the gasification temperature. During commercial operation of the gasifier on B-wood, the gasification temperature was lowered stepwise, to test the behaviour of process and equipment at these temperatures. The results included: equipment behaved well, the gasification process ran well and was stable. The steam production went down. Fouling of the gas cooler was much less. The time intervals between off-line cleaning actions at least doubled (still on B-wood).

Therefore, testing continued with gasification of RDF/B-wood mixture with a duration test with 40% RDF. Fuel logistics: no problems. Gasification (at 750°C) went well. Gas cooler fouling was much lower but still too high. Off-line cleaning was necessary after about 200 operating hours. The gas cooler was blocked in the highest temperature section, where the spaces between the cooling panels were the smallest. The ash amounts are bigger than with B-wood, but they behave well. The conclusion: upper section of the gas cooler had to be modified by enlarging the space between the panels.

The present status of the testing is that gas cooler modification has been executed. The next test will be on a 50/50 mixture of RDF and B-wood. However, another line of development is also going on. A new support system for biomass is being prepared by the government. Thus, operation on B-wood may become commercially attractive again. Still operation on a RDF/B-wood mixture will perhaps be even more attractive. Therefore the development will continue with the application of alternative fuels in the gasifier.

The overall conclusions were that with gasification of biomass for co-firing the gas has in the end become successful, however, it has needed quite some development effort, time and money. Cooling and cleaning of the gas are the most difficult process steps. Lowering the gasification temperature to 750°C is very positive for the fouling behaviour in the gas cooler. Continuous gasification of an RDF/B-wood mixture will be tested in the last months of 2014.

11.2 Rentech-Silvagas and Burlington plant

SilvaGas Corporation (formerly FERCO Enterprises) was a renewable energy technology company, headquartered in Atlanta and engaged in the development of clean energy and waste disposal solutions.

The company acquired the exclusive license to the patented SilvaGas process. The company and all technology were further acquired by Rentech, Inc. The company is not active in pursuing gasification projects on commercial terms and conditions.

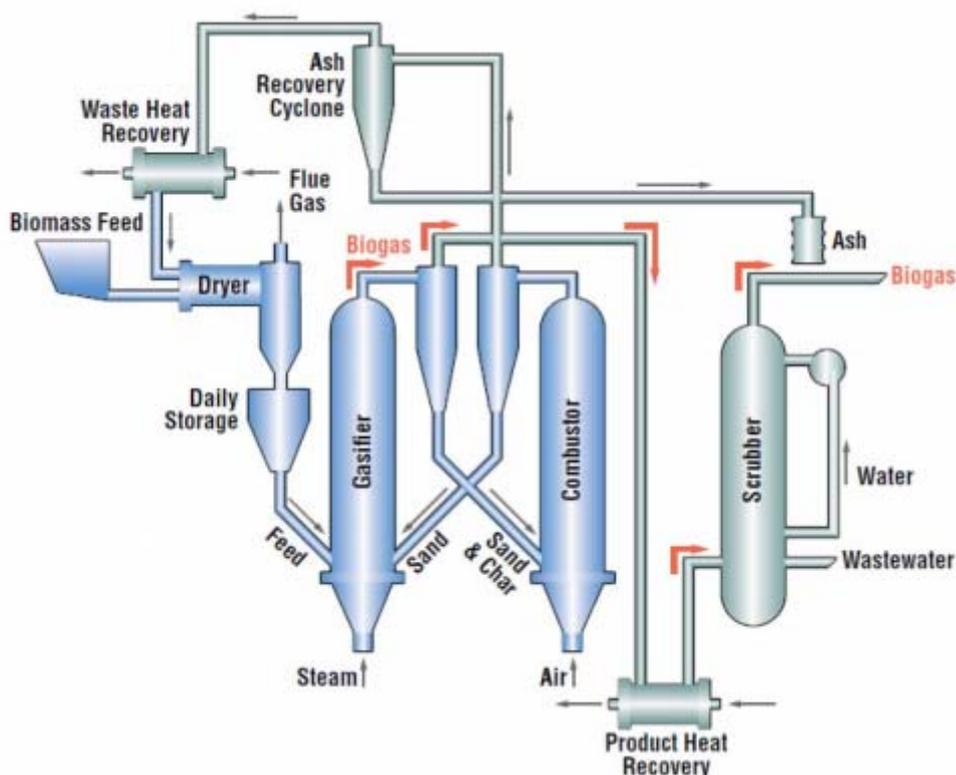
11.2.1 Technology

The Rentech-SilvaGas process was originally developed at the Battelle Memorial Institute in Columbus, Ohio in the 1980s. Battelle is one of the largest research institutions in the world.

Battelle maintained and operated a 10 tonnes per day Process Research Unit (PRU) of the Rentech-SilvaGas process. To date more than 22 000 hours of operational testing was completed in the PRU on a wide range of biomass feedstocks. This pilot plant made history in 1994 with the first integrated operation of a gas combustion turbine on 100% biomass derived gas.

The Rentech-SilvaGas process generates clean medium Btu gas through the gasification of biomass feedstock, including forestry, pulp and paper residue, agricultural byproducts, municipal solid waste and energy crops. The Rentech-SilvaGas biomass gasification process produces a gas that can be substituted directly for natural gas in most applications, including conventional gas turbines, advanced gas turbines and fuel cells.

The SilvaGas gasification system, in short, is a process operated at atmospheric pressure and consists of two CFB units. The primary CFB is the gasifier in which the fast pyrolysis/gasification of the biomass takes place. The heat necessary for the reactions is brought to the biomass fuel by hot sand.



Figur 83. Schematisk bild av SilvaGas-processen med dubbla CFB-reaktorer (Ref. SilvaGas).

Figure 83. Schematic of the SilvaGas process with twin CFB reactors (Ref. SilvaGas).

The process uses two physically separate reactors; the first is a gasification reactor (pyrolyzer), in which the biomass is converted into a medium-Btu gas and residual char. The second is a combustion reactor where the char burns to provide heat for gasification reactions. The process takes advantage of the inherently high reactivity of biomass feedstocks.

Circulating sand is used as the working medium to transfer heat between the gasifier and the combustor. The gasifier heats the wood chips to about 830°C in hot sand until the wood breaks apart into its constituent chemical components. The gasifier is a circulating fluid bed, and the combustor is a bubbling fluidised bed.

The gasifier reactions create a considerable amount of char. This flows with the sand to the second CFB in where the char is combusted with air to heat up the sand and the sand is thereafter recycled to the gasifier. The hot flue gases from the second CFB are used for steam production and for fuel drying.

The design of the gasifier and the combustor are rather complicated with an intricate cyclone system that adds to the complexity of the system and makes the operability and maintenance of the plant a rather difficult and expensive task.

The cyclone system, after the gasifier, separates the sand and char from the gases. The solids are then fed directly into the combustor, whereas the gases are fed to a scrubber for further cleaning to make sure that the gas is free of traces of tars and particulates.

A key feature with the process is the ability to be highly flexible in that it can accommodate a wide variety of feedstocks of varying moisture content without impacting the heating value product gas.

11.2.2 Operational experience

Following the conclusion of pilot testing, the SilvaGas Process was demonstrated at commercial size at the McNeil Generation Station in Burlington, Vermont, at that time one of the largest wood-fired power generation plants in the world. Construction of the Vermont facility was completed in 1997. The operational results have however not been as expected.

The commercial scale demonstration of the SilvaGas process at the McNeil Generating station was designed for 200 tonnes per day of biomass feed (dry basis) but was operated in excess of 300 tonnes per day (dry basis). The plant has accumulated more than 1000 operating hours, however, during many years.

Burlington Electric Department's (BED) McNeil station was selected as the site for this demonstration plant. The McNeil station uses conventional biomass combustion technology. The gas produced from the gasifier was used as a co-fired fuel in the existing McNeil power boilers.

The first operation of the Vermont gasifier in full steam gasification occurred in August of 1999. During the start-up period, numerous design and operational changes to the plant were necessary to improve the performance of process auxiliary systems. No problems with the core process were encountered throughout the start-up period, but a number of improvements to process auxiliary systems were made. These included materials handling, solids separation, and product gas scrubbing.

In a further development of the SilvaGas process, a novel hot-gas conditioning catalyst (DN34) was developed that converts condensable products (tars) to lower molecular weight, and therefore, essentially non-condensable forms. This catalyst then allows for a much reduced loading on any scrubbing operation due to the elimination of the higher molecular weight materials. Test data generated during operation of this system showed that up to 90% of the "tar" produced in the gasifier is destroyed in the catalyst at normal operating temperatures.



Figur 84. Flygfoto på förgasaren i Vermont (Ref. Silvagas).

Figure 84. Aerial photograph of the Vermont gasification plant (Ref. Silvagas).

During the initial testing runs, a number of problems were identified concerning the fuel feeding system, the scrubber bottom and the pumping systems from the scrubber. Therefore, the gasifier plant has been down most of the time for maintenance and for introducing several modifications.

One important problem was the designed scrubber-evaporative circuit (especially the Venturi scrubber) which could not handle the increasing amount of attrited bed material. This material behaves like silt that forms a dense phase occupying a smaller volume of the scrubber tank. This problem requires rebuilding the bottom of the scrubber and replacing the pumping systems. The pumping has also been revised by replacing the diaphragm pumps with travelling cavity pumps that can handle the much denser silt phase.

The project ended in 2001, and McNeil mothballed the demonstration's gasifier. Part of the reason Burlington Electric Department did not continue with the gasification project was the low potential of agricultural residue to utilize as a feedstock in Vermont.

12 Discussion and analysis

12.1 Gasification technology maturity

There are many ways to utilize biomass as an energy source so many efforts are put to develop different efficient technologies. Biomass gasification is one of the thermal biomass conversion processes. It can be used for producing power and heat or for the production of different fuels with higher energy content than biomass. It can provide gaseous and liquid form of fuel that can be used as a substitute for oil derivatives.

Biomass gasification is an emerging commercial technology evolving out of intensive research and development in the 1970s and 1980s, although its developmental roots go back 180 years ago. Despite the fact that there are plenty of gasifiers around the world, most of them are coal based while the biomass gasification systems from small to large are commercially available only in last five years.

The exceptions are CFB limekiln gasifiers and fix-bed updraft Bioneer gasification technology from the 1980s. However, a few countries have embraced the demonstration and commercial biomass gasification plants for heat and power generation. Nonetheless, the first large-scale commercial plant for transport fuel production is still not in operation.

The R&D in biomass gasification started in very small scale and with limited resources after the first oil crisis in 1972. The available fundamental thermochemical data were very limited and old-fashioned. The first interest was therefore to generation such data, reaction rates, product distribution etc.

The first market intended was liquid fuels especially methanol. The technical background was that in USA a lot of modern R&D had started on coal gasification to SNG from small scale research to several pilot plants. Only one full scale plant was built in North Dakota and based on the German Lurgi gasifier.

The interest diminished during the 1970s when it was obvious that no short-term lack of natural gas could be seen. Most of the developments were stopped. A few looked for new areas to apply the knowledge. GTI (former IGT) is one example who turned to biomass and also peat after some exchange with Royal Institute of Technology in Stockholm. The U-Gas technology was modified and applied for the new fuels as the Renugas process: That became the base for Tampella and later Carbona/Andritz gasification.

Only after the second oil crises in 1978 the resources in EEC, USA, Sweden and Finland increased very rapidly as the oil price then was almost 10 times higher than 1971. The politicians wanted to see rapid process scale up with a focus on liquid fuels like methanol.

The commercial situation for biomass gasification has been varying over the last 40 years depending mainly on the oil price and electricity price. Mostly with a weak market short-term, but with hope for a better long-term market. Within the biomass field for heat and electricity combustion technologies have been the major option and hence a strong competitor to gasification. In the early 1980s a possible market for biomass gasification was identified. A first installation of wood powder combustion in a lime kiln in Piteå identified some increased ash components in the liquor cycle that could affect the concentration of the liquor.

Gasification was an option where most of the ash could be separated before combustion. Ahlström was the first to develop a CFB gasifier for this purpose. High content of tar/hydrocarbons with high pre heat temperature of the gasification air made the LCV adequate for the limekiln (when fired at high temperature). Several gasifiers were built. Also Studsvik/Fläkt and Götaverken developed similar technologies.

Even if most of the CHP plants used combustion technologies Bioneer in Finland found a niche market. The Bioneer gasification technology were well proven commercially already during the 1980s. The limiting factor for selling further plants both for Bioneer and CFB gasifiers have been the low oil price and competition with combustion technologies. Extensive pilot testing with a low scale up factor to commercial size explain the success with several commercial gasifiers in a few years' time during the 1980s. The upscaling took usually place in two steps after laboratory testing, first pilot plant and then the first small commercial step. That was the case for Bioneer, as well as the CFB lime kiln gasifiers.

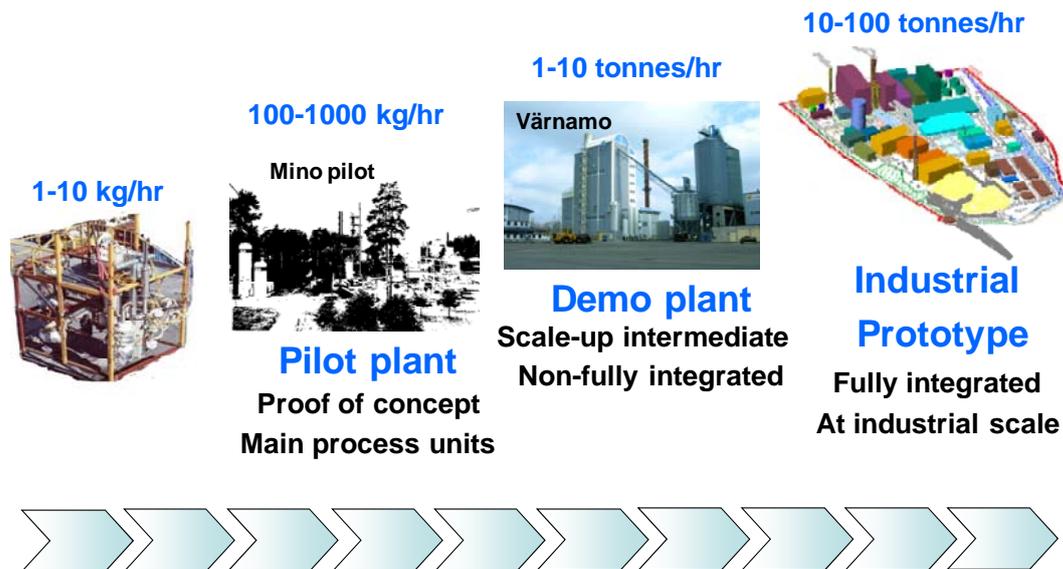
This is a strong evidence that one-step gasifiers without further gas cleaning can be reliable and rather quickly started up even with fully automatic operation. The later experience with the multistep Novel process with advanced gas cleaning illustrates that this is much more difficult and needs more time and money for commissioning.

During the 1990s when the oil price still were reasonably low the electricity priced increased and further increase were expected in the future. Developers turned to engines and gas turbines to generate electricity more efficient from biomass. That again focused on the gas cleaning problems with tar as a main issue for biomass. Two main routes were followed catalytic decomposition or scrubbing with organic solvent (RME or tar/tar fraction). The fundamental option for catalytic tar cracking/reforming was showed already in the 1970s at the Royal Institute of Technology (KTH), Stockholm in laboratory scale. Steam reforming catalysts based on nickel can convert both the heavy tar and ammonia very efficiently.

Scale up to pilot size 2.5 MWf (Mino) showed that high temperature filters could protect a catalytic bed of nickel catalyst at pressures for syngas. Later scale-up and catalyst development at VTT also showed dirty gas catalysis without filter can be an option in monolithic multi-channel supports. Dolomite was also showed to be an effective tar catalyst for tar at KTH in laboratory scale 1978. The dolomite is only active in its calcined form.

Further development and up scaling have mainly tried to solve the problem that the calcined dolomite generally is very brittle and generates a fine dust. The recalcining at high pressure and in the cooling train also led to blocking in the coolers. Those problems are not yet fully overcome.

The development of syngas and liquid biofuels are both large scale and multi-step. The scale-up have to be taken in several steps which are costly and time consuming. The economic benefit is only at the best long term. The process is illustrated with the planned Värnamo development, below.



Figur 85. Illustration av utvecklingsvägen för Värnamo-konceptet (Ref. VVBGC).

Figure 85. Illustration of development path for Värnamo plant concept (Ref. VVBGC).

After tests in laboratory scale to develop new steps scale up to pilot plant which is a relatively complete part of the core process but often with simplified handling and fuel choice. The operational times are several thousands of hours and separate runs of hundreds of hours. The demonstration plant verify the complete plant at a scale large enough for final scale up to commercial size

Even when the complete technology is demonstrated at pilot plant scale a long time a lot of costs still have to be taken. With this background only rich and long-term players can take the risk. Even for strong companies with relatively well proven technology e.g. Foster Wheeler the commercial risk on a weak market can motivate them not to offer on the few existing projects.



Figur 86. Illustration of tidslängden för utveckling till utplacering (Ref. VVBGC).

Figure 86. Illustration of development time span for the deployment (Ref. VVBGC).

The later experience with the multistep Novel process with advanced gas cleaning illustrate that this is much more difficult and needs more time and money for commissioning.

Waste gasification has always been potentially profitable and thus a lot of demonstration plant has been built from the 1960s until present day. Almost all of them have failed. Many projects have been driven by parties with very limited knowledge of waste. Waste gasification includes a lot of handling problems, permissions problems and most of the known gasification problems (high ash content of low melting ash, emission precursors like chlorine, nitrogen and sulphur).

Today the commercial development is led by waste to energy (cogeneration) and waste to liquid fuels (Enerkem and methanol) as waste projects are profitable. The predominant technology is fluid-bed gasification with more or less gas cleaning. The Enerkem technology is just now taking the step to commercial scale based on pilot and demonstration experience. The final scale up factor is low about three times. Both these facts can lead to a rather successful commissioning despite the process consists of a long series of steps. A very strong point is the focus at the profitable short-term market for waste gasification.

That points to the fact that technology development to commercial scale only to a minor part is technology based. Commercial strength and partnership are also of major importance. Most technologies have initial problems in the demonstration and commercial scale. Only the partnership or companies that can take the time and cost to sort out the problems can find a long term success. These costs can be taken by the developer, the construction company or the customer company depending on the strength. If no one has that possibility the development will be stopped with major problems to be restarted.

12.2 Impact of biomass as fuel on gas cleaning

Biomass contains a wide range of elements that may react to form potentially harmful deposits in gasification systems and downstream processes. The 'mix' of elements in the fuel gases produced in a gasification process will be highly dependent on the biomass fuel composition. Therefore in the process design it is essential to investigate the effects of possible deposits will have on equipment and the components in such systems. From such information, fuel specifications can be derived, to ensure adequate lives for components.

From plant data, filter temperatures below 400°C may be required to reduce contaminants. In other cases, supplementary gas cleaning stages or the use of a scrubber may be required or the use of a scrubber to meet required targets, impacting significantly on costs and cycle efficiency. The vital points arising from the above analysis are summarised as follows:

- Fuel composition: the critical contaminants species are S, Cl, alkalis and trace metals and their behaviour is similar for combustion plants with the exception of being in reduced form in the product gas.
- Fuel gas compositions vary significantly between gasification systems at the trace contaminant level (as well as the frequently reported bulk gas composition level).
- Most trace and alkali metals are more volatile in gasification systems than in combustion systems – the same classification of volatility as for combustion gases is not applicable (different species are volatile).
- S and Cl levels (both absolute and relative), as well as operating pressure and gasification process can influence the volatility of trace and alkali metal species.
- The high levels of trace metals present in gasifier product gases can be reduced by use of low filter operating temperatures (e.g. 250-450°C dependent on the gasification system).

In the case of a gas burner and heat exchangers the performance is vital to the overall plant efficiency and economic viability. However, within these systems hot corrosion and/or erosion are likely to be life limiting. The degradation of materials in such systems has been the subject of many investigations during the past 40 years and many similar types of materials degradation can be expected.

However, the contaminant levels are different, there are additional as well as absent species and the sources/forms of the contaminant species also differ. Fuel-derived particles can cause either erosion damage or deposition depending on the particles' size and composition, as well as aerofoil design and operating conditions. Corrosion can result from the combined effects of gaseous species (e.g. SO_x and HCl) and deposits formed by condensation from the vapour phase (e.g. alkalis and other trace metal species) and/or particle impaction and sticking.

The mode of corrosion damage is highly dependent on the local component environment. Conventionally, the metal vapour species of most concern are alkalis (mainly Na) and S.

If a water or chemical scrubber is included (e.g. for ammonia removal), the levels of these contaminants will be significantly reduced whereas a hot dry cleaning approach will potentially lead to higher levels, depending on the operating temperature of the filter. The effects of different fuels on the levels of contaminant vapour phase species, deposition fluxes and deposit compositions (e.g. melting points) requires careful consideration for each process and fuel.

From the above, it is clear that care is needed in designing the process flow sheets for biomass systems. In particular, those for fuels such as wheat straw, with very high K and Cl levels, require careful consideration of the removal of fuel contaminants so that a reliable and cost effective gas cleaning approach can be adopted.

For the lower efficiency atmospheric pressure systems, scrubbing to remove some of the residual tar and ammonia should also reduce significantly the water soluble trace contaminants such as KCl. But as the gas is cooled substantially prior to scrubbing to minimise energy losses and to meet scrubber entry requirements, many of the trace contaminants may well have condensed onto entrained particulates or component surfaces, before the gas reaches the scrubber. From the burner perspective, the scrubbed fuel gas should not present any problems as nearly all fuel-borne contaminants should have been removed.

The most important factors for choice of technology are plant size and application. The physical particle size and moisture content are also very important for the choice of technology. Fixed-bed technology needs large particle and maximum amount of fines.

The following sub-chapter details plants with gasification followed with limited gas cleaning and then with further advanced gas cleaning technology. The impacts are discussed and described on both the criteria of the gasification technology and the gas cleaning and subsequent applications.

12.3 Limited gas cleaning

12.3.1 Updraft gasifier – Bioneer

The Bioneer technology was developed in Finland during the early eighties in a pilot plant with capacity of 1.5 MWf. During the 80s a total of eight gasifiers were erected in seven different plants. Two plants were built in the northern Sweden in Lit outside Östersund for the dryer to a chip board (MDF) factory and one plant in Vilhelmina for district heating. The other plants were built in Finland, with the first in operation from 1986 and the others shortly thereafter. One of those plants (Jalasjärvi) had already in 2005 accumulated 145 000 hours of operation, and by now it should be over 200 000 hours in that plant. The total accumulated operating hours for these Bioneer plants would today account for at least 1.5 million hours, which in itself is a historic achievement.

The total accumulated operating hours are calculated as in principle non-stop operation until 2013 with 6 weeks maintenance stoppage each year from year 1986, apart from the first couple of years with lower performance. The total number of operational hours in Lit are about 400 000 together. The main conclusion is that Bioneer have more accumulated operational time than any other biomass gasifier together with the CFB limekiln gasifiers, but no sales have taken place in the last 20 years. That is probably due to the direct competition with combustion technologies for heat production.

12.3.2 Limekiln CFB gasifier

Ahlström invented the CFB biomass gasifier coupled to a limekiln in the forest industry after the second oil crisis 1978 when the oil price was very high. The invention to reach a high enough heating value on the gas for a limekiln was accomplished with:

1. The fuel was dried to less than 10% moisture
2. The gasification air was preheated to high temperature with the hot fuel gas
3. The CFB gasifiers with “flash pyrolysis at high temperature” produced a lot hydrocarbons (including tar) with high heating value
4. The fuel gas was fed hot to the burner.

The atmospheric CFB gasification system developed by Ahlström consists of a gasification reactor, a cyclone to separate the circulating-bed material from the gas, and a return pipe to return the circulating material to the bottom part of the gasifier. All these components are entirely refractory-lined. From the cyclone, the hot product gas flows into a heat exchanger/air preheater located below the cyclone.

Gasification air is blown with a high-pressure air fan through an air distribution grid at the bottom of the reactor, below a bed of particles. The air velocity is high enough to fluidize the bed particles and convey some of them out of the reactor and into the cyclone, where most of the solids are separated from the gas and returned to the lower part of the gasifier. The cyclone has a special design in the Foster Wheeler gasifiers, both the gas and the solids are extracted from the bottom of the cyclone.

The CFB/gasifiers starting from the early lime kiln gasifiers are the leading type of biomass gasifiers considering the operational experience on biomass as well as other fuels like RDF. The CFB gasifiers have more than 20 years of operational experience even if most of them now are closed (e.g. the Swedish plants). As the main application (lime kilns) are industrial with up to 8000 h operation per year these CFB-gasifiers have accumulated more operational time than any other type of biomass gasifiers.

12.4 Advanced gas cleaning

12.4.1 Harboøre

Babcock & Wilcox Vølund started already in 1988 to develop a fixed-bed gasifier. The plant is situated in Harboøre and owned and operated by Vølund with a long term contract to sell district heating to a 560 customers and local municipal buildings.

After several years of development work the first gasification plant was put into commercial operation in 1993. However, there was a long optimization process and not until 1996 the gasification was considered commercial with steady operation. The gasifier reactor has now been in operation for more than 150 000 hours. The plant operates in automatic mode and with personal only during day-time.

The initial experience was very poor and even after rebuilding it took several years to reach the goal for unmanned operation. Today the availability is remarkably good and the technology have to be considered technically mature.

12.4.2 Kokemäki

To make it possible to use the updraft gasifier Bioneer technology for gas engines and other advanced applications Condens OY initiated a development program with VTT based on the experience at VTT with catalytic tar cracking with monolith nickel catalysts (mainly for FB-gasifiers). The technology was developed at small scale at VTT. The construction work for the first Novel plant was completed in April 2005. The commissioning lasted until the end of 2006. However, the gasifier and boiler took only two months for commissioning, from April to May 2005. Gas cleaning and heat recovery was commissioned by the end of August 2005.

Commissioning and operation with one engine continued during 2006 and the two other engines were taken into operation end of 2006. When the advanced personnel from VTT staff left, the number of disturbances and operational fall-out increased. This led to severe cost-increase, ultimately to the closure of the plant.

The Bioneer and Novel experiences provides strong evidence that one-step gasifiers without further gas cleaning can be reliable and rather quickly started-up even with fully automatic operation. The later experience with the multistep Novel process with advanced gas cleaning illustrate that this is a much more difficult gasification route and needs more time and money for commissioning.

12.4.3 Güssing

The process from Repotec was developed during the 90s at the Technical University of Vienna and resembled thermodynamically the Rentech-SilvaGas process but with different mechanical design. The company Repotec was founded in July 2001 to commercialise the gasification technology developed within the plant constructed in Güssing. By Nov. 2001 the technology had been implemented and the plant started up in Güssing.

The two-stage, combined fluidised bed gasifier and CFB combustion process has demonstrated exceptional rapidity of success in scaling-up the laboratory scale unit to a commercial demonstration plant. The plant has operated successfully for a long time and continues to be of high interest for further development. The availability has increased over the years. The plant has not been rebuilt and upgraded as the sister plant in Oberwart and thus suffers from more service needs and lower availability.

12.4.4 Oberwart

The plant in Oberwart was rebuilt in 2012. All known problems were tried to be solved. The rebuild included a redesign of the coolers that made them more available for cleaning when needed. After new start up and trimming very high availability could be achieved during 2013. The whole procedure from first start up to acceptable availability took five years. In conclusion, the start-up problem can be significant even in the second plant if technology transfer is not secured.

The whole commissioning procedure in this case took a very long time (several years) and there was a need for someone to take the losses during that period. In Oberwart the plant owner a local utility Energi Burgenland have taken most of the costs.

12.4.5 Skive

Carbona has supplied a 30 MWf biomass gasification based CHP plant to Skive Fjernvarme in Denmark. The plant was commissioned in Sept 2007 and had the first couple of years a long commissioning period with major technical challenges. Since 2009 the accumulated operating time is 20 000 hours with an average availability of 70-80%. After the plant was commissioned late 2007 the availability was very low and not up to design values. High availability has then been achieved after major trimming and rebuilding of the catalytic system as well as changing of catalyst. That process took several years and at significant costs. For a new similar plant, the availability would be +20% with a redesign of the reformer, thus some 95% availability.

12.4.6 Värnamo

The Swedish power company, Sydkraft (now E.ON), constructed in the 1990s a co-generation plant at Värnamo, Sweden to demonstrate the Bioflow technology with combined cycle (IGCC) technology. The start-up phase was completed during spring 1996 and followed with a four-year demonstration programme. The accumulated operating experience amounts to about 8500 hours of gasification runs and about 3600 hours of operation as a fully integrated plant as per the end of 1999. The test runs were very successful and the plant was operated on different wood fuels as well as straw and RDF.

Most of the problems after initial commissioning were centred on the ceramic hot gas filter. The ceramic filter showed good filtration efficiency, with stable pressure drop. However, after more than 1200 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.

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. Complete combustion of the hydrocarbons was always achieved with emissions between 1 and 4 ppm only, whereas a slightly high value of CO was observed with values up to and sometimes even above 200 ppm on part-load operation.

The conclusions from the demonstration program are the following. The difficulties encountered initially in the Värnamo project were overcome after a couple of years of intense commissioning and testing. Principal results achieved were:

- 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
- NO_x 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 plants.

Some aspects need further development before full scale application like the high bed material consumption which is not commercially acceptable.

12.5 Deep gas cleaning

12.5.1 Varkaus

The Finnish joint venture NSE Biofuels built a demonstration plant in Varkaus, Finland, to demonstrate long term gas production and gas cleaning to meet the requirements of FT-synthesis.

Test runs included testing at different gasification temperatures ranging from 860 to 940°C and different oxygen/steam ratios. The oxygen content of the fluidizing agent into the wind box was varied between 23% and 50%-w, typical value being around 45 %-w. The fuel consisted of different types of woody biomass: wood chips, first felling wood, bark and forest residues.

The cumulative operation hours of the oxygen-steam gasification were more than 9000 hours by the beginning of June 2011 and for the 5 MW slip-stream gas cleaning plant the operation hours were more than 5500 hours. The final FT test unit had a size of about 0.1 MW. This test has been named demonstration but is more of an intelligent and less costly way to run a long-term test at pilot-scale. A complete pressurized demonstration plant might be needed before commercial application.

12.5.2 Chicago

GTI has together with Andritz/Carbona, Haldor Topsøe, UPM-Kymmene and Conoco Phillips built in 2004 a pressurised pilot plant in Chicago. The operational experience for the pressurised BFB pilot gasifier has been said to be overall good, but with a weak start. The fuel feed is wood pellets generating a stable gas with constant gas composition and heating value. The tar content was said to be low and the filtration performance good.

The plant was later retrofitted with a methanol to gasoline unit and in October 2013 the team produced about 4000 gallons (15 400 litres) of gasoline suitable for use as a gasoline blend stock. This was used for single-engine emissions testing, demonstrating that renewable gasoline would meet EPA standards in blends up to 80%.

The final test campaign in March 2014 produced sufficient quantities for testing to prove that the gasoline can be used in existing automobile engines. Around 7770 gallons have been sent to a blending facility in Michigan to prepare it for a fleet test at the Transportation Research Center in East Liberty, Ohio.

The critical process areas for further development of a gasification plant are foremost the reformer and gas filter and gas coolers, which is also where much research activities are placed today.

12.5.3 Enerkem – Westbury and Edmonton

Enerkem has validated its current, proprietary technology over a period of 10 years using solid urban waste and other types of feedstock in pilot plant scale and demonstration scale.

The current development for the gasification-based process technology is to convert sorted MSW and residues from the forest and agricultural industries into transportation fuels, high-value chemicals and electricity.

The scale up factor between Pilot and Demo was <10 and it has been kept at <10 from Demo to Commercial in Edmonton. Such prudent approach in scaling up led to a rather successful commissioning at Westbury, despite that the process consists of a long series of steps. It is also proceeding well in Edmonton where syngas and methanol production are expected to take place in the autumn of 2014.

13 Commercial perspectives

13.1 Introduction

This chapter details the commercial perspectives of a gasification plant. Before an investment decision on a new CHP plant there are a number of conditions to consider that can affect the choice of technology solution, e.g. the following general examples:

- Operating conditions – power capacity and operational hours per year?
- Fuel supply – availability and prices?
- Site location issues, proximity to housing or other sensitive environment?
- Available surface area, permitted building height?
- Transport possibilities to and from the facility?
- Environmental permit constraints – emissions, noise and transports etc?

The next step is an evaluation of various technology concept solutions for plant performance, environmental and climate impact, plant economy, profitability and risk.

The gasification technology is fuel-flexible. The fuel can consist of both waste and solid biofuels. In addition, a specific benefit is the potential for a high electricity yield on a given heating demand.

The plants can be built in sizes ranging from a few to several hundred MW. The gasification reactor is smaller than a corresponding boiler as air demand is lower with gasification in contrast to combustion.

Gasification has the potential to meet the same environmental standards as conventional combustion. The total efficiency is marginally lower than during combustion. A gasification plant can be equipped with flue gas condensation, as with combustion plants. These conditions make the technology suitable for both base-load and intermediate power load in a district heating network.

Despite these advantages, the number of commercial gasification plants in Sweden and elsewhere in Europe is limited. Currently, almost all waste and biomass-fired cogeneration plants are built with steam turbine cycle for base and intermediate load in Sweden. This technology is commercial and proven. There is extensive experience in plants with good track records. In recent years the trend has been toward more fuel-flexible plants, whereas the power yield has improved marginally.

One strategy to increase power production from conventional CHP plants has been to extend the operating time by finding ways to dispose the heat for a longer period of time during the year. One such way is to integrate the electricity and heat production with other processes such as the production of refined fuels and transport fuels.

One plausible reason for the lack of a major impact of gasification technology, despite major investments in research, development and demonstration, is the limited number of commercial reference plants. Operational experience is somewhat poor compared to conventional technology in many cases, although there are important exceptions. Sufficient knowledge basis are so far almost non-existing for a fair assessment of the availability, durability and maintenance costs.

The estimated operating availability is of utmost importance when evaluating different technology alternatives. Failure of a larger base-load plant during high-load periods may give major disruptions in heat deliveries to the customers. The value of an incremental power yield gain is diminished in a matter of only a few days unavailability of a base-load or medium-load reactor.

Moreover, it is also somewhat uncertain if there are suppliers to undertake an EPC contract with the gasification technology which gives the highest power yield – BIGGC (Biomass Integrated Gasification Combined Cycle). Foster Wheeler and Andritz are plausible EPC contractors and have capability with needed experiences and technology but reference plants are missing.

The gasification technology has also some disadvantages compared to conventional technologies that can influence an investment decision. For instance, gasification of waste and biomass in a fluidised-bed reactor requires more fuel pre-treatment than conventional CHP with a boiler.

Gasification of waste in a fluidized bed requires in most cases the sorting of a combustible fraction, consisting of wood, paper and plastic, crushing and screening. This fraction so-called RDF generally have a moisture content <30% why not drying prior to gasification is necessary. In the future, this handling may probably not be distinctive to combustion with a grate-boiler due to sorting out of the food fraction from the waste.

Biofuels like *grot* and bark with moisture contents of about 50% must typically be dried prior to gasification (however, not for all gasification reactors). Nowadays, the drying is done preferably with belt dryer that can be supplied with district heat, which is positive. This type of dryer is however rather large and takes up a lot surface area, which can be a problem for certain sites. At certain times the large volume of moist air ventilation (steam plumes) may lead to complaints from local residents if the facility is located near settlements. The same applies in the event of odour problems from the dryer.

Gasification plants must also be equipped with torch for emergency stop. This can be built-in to reduce visibility and noise. Nonetheless, it is a new feature of the cityscape that may pose limitations. One advantage with gasification is that the reactor is smaller than the combustion boiler, i.e., the building can be smaller in the surface area.

The possibilities for the gasification technology to be established for base or medium load production could decline over a few years because the future market potential for CHP plants may soon be reached with conventional technologies.

The current electricity production from Swedish CHP plants is about 8-9 TWh/year. The potential for future expansion of cogeneration has been assessed in several studies and is estimated to be about 5 TWh by 2020 and a further marginal increase in 2030. The design life of the cogeneration plants varies but is usually between 30 and 50 years. Currently ten new cogeneration plants are being built around Sweden. There are plans and projects for a further 20 plants.

Long lead times – usually five to ten years – from plant concept to commercial operation makes it very difficult to establish new production that is not fully developed. The risk may be regarded as too high even if the technology is deemed to be fuel flexible and give high power yields. This is especially true as the price of electricity is likely to be relatively low for some years to come.

In addition, there is a consensus that the heat demand will decrease in the future because of increased energy efficiency among end users, warmer climate and increased competition mainly from distributed heat with heat pumps and wood pellets. This occurs while there is an ambition to increase resource efficiency and utilize waste heat from industries, various businesses and properties to district heating. One consequence of this is that the need for new heat production decreases – especially in areas with low population growth or decrease.

The markets where gasification could potentially attract the most interest at present are:

- Gasification of biofuels/RDF and co-firing with fossil fuels in an existing CHP plant
- Gasification of RDF and firing in a gas CHP plant with high steam data
- Small scale power production
- Biomass Integrated Gasification with Combined Cycle – BIGCC
- Biomass to Liquids – BTL where biomass based synthesis products for the transport sector is very promising to replace fossil fuels.

13.2 Atmospheric gasification

13.2.1 Biomass as fuel

During the mid-1980s, the technology for atmospheric gasification of biomass in CFB gasifier was developed. The driving force was the high oil prices. The produced gas replaced heavy oil in lime kilns. Although several plants have been shut down because of declining oil prices there are references with extensive experience. There is also today new installations with this application like Andritz with a 48 MWf gasifier in Joutseno and Valmet with the Indonesian project of 2x110 MWf.

Continued development of the technology has led to new possible applications of which partly converted fossil-fired cogeneration units could be interesting. This utilizes biomass gasification or RDF as an advantage. The product gas is then co-combusted with regular fuel in the existing boiler.

The technology has many advantages. The investment costs for a partial conversion of fossil-fuelled plant can be kept down as the existing boiler and turbine can still be used. Most often, also the high electrical efficiency maintained. The technology is fuel flexible – bark, *grot*, peat and RDF can be used. Pre-treatment of the fuels may nevertheless be required. Wet biomass must often be dried, crushed and sieved.

In the case of gasification of waste a sorted fraction must be used, called RDF. If RDF is used a fuel for gasification the boiler must be classed as a waste fired boiler or co-fired boiler. Which measures are necessary for the classification and the specific capital cost investment will be individual and depends on e.g. the residence times, design and choice of material of the existing boiler and the flue gas cleaning systems.

This gasification technology and application is considered mature and commercial. There are a few commercial establishments, both shut down and in operation, with a fossil fuel conversion of up to 25% with renewable fuels.

The possibility to implement the technology in Sweden is now limited as there is almost no coal-fired thermal power plants left which remains in operation. Oil-fired plants are also possible for partial conversion with same design concept. For plants with high steam data, however it is assumed that, the load and electrical yield will be limited due to corrosion and risk for coating and fouling.

For partial conversion of pulverized coal-fired condensing power plants, the technology is interesting if there are sufficient incentives/instruments to increase the use of renewable fuels. A strong competitor, however, is wood powder/torrefied biomass which has low specific capital cost investment requirements.

13.2.2 RDF as fuel

After developing the technology for the purification of the product gas from alkali Valmet now markets an interesting concept that allows a high electrical yield with gasification of RDF with subsequent combustion in a gas-fired cogeneration plant and conventional flue gas cleaning (as seen in the Vaasa CHP plant).

Steam data and electrical efficiency of the gas boiler equals those of biomass-fired cogeneration plants. This stage of development means that electricity production will be considerably higher than for conventional waste/RDF combustion in a grate or a CFB-fired CHP plant with today's power yields.

With this technology it is possible to increase the net electrical yield from typically 19-23% as with conventional combustion to 25-30%. The total efficiency will be a few percentage points lower because of increased internal demand for electricity and heat to drive the process.

Once the technology is fully mature, it is possible to reduce both investment and operation and maintenance costs significantly. With increasing sorting and recycling of food waste and different materials in the future, the conditions for this technology will be further improved in comparison with conventional grate as this alone will not be burdened by the costs of extensive reprocessing of the waste to be gasified.

The increased recycling of materials, waste prevention, landfill bans, and sorting of food waste to biogas production, however, are measures that will reduce the volumes of waste going to incineration. Another fact is that in the current situation, waste incineration with conventional technology has been expanded to such an extent that there is excess capacity in Sweden. Currently, all Swedish combustible household waste is used already for production of energy carriers.

There are two factors that may counteract the above obstacles for an implementation of this technology in Sweden. Some of the waste incineration plants are close to reaching their full technical lifetime and needs to be replaced. There are thus opportunities for this gasification technology. Another possibility for a commercial window of opportunity is that the energy conversion of waste continues to increase, fuelled by import waste fuels.

13.3 Small scale power production

There are a number of suppliers and concepts for small-scale power production (<10 MWe) based on gasification. The small-scale gasification technology often comprise of a fixed bed gasifier or smaller CFB with subsequent gas cleaning and combustion of the product gas in a gas engine.

Several countries in the EU today provide support to both the development and demonstration of small-scale power and heat production with gasification technology. These plants are often very complex and include the necessary gas cleaning, gas engine and sometimes also ORC technology to boost the power yield. Despite that the technology has been demonstrated (built and rebuilt) at a few commercial plants the relatively low availability proves the technology as not yet fully mature. However, there are numerous smaller, similar plants, which have proved high performances. These plants are however built in different settings than for the selection criteria of this study.

Conventional biomass-based small-scale combustion and steam turbine (Rankine cycle) may at best reach net electrical efficiency of some 25%, and it is very difficult to obtain a substantial higher power yield. On the other hand, biomass gasification and combustion in gas engine concepts have reported power yields ranging 25-35%.

Investment and operation & maintenance costs will be high for all fuel-based, small-scale CHP plants. There are also some needs for further development of small-scale CHP gasification technology. Small-scale power and heat can be interesting in the future when the technology has become mature, electricity prices are higher than today and if the heat demand is smaller for the power generation.

13.4 BIGCC

Pressurised, biomass gasification integrated with gas and steam turbine cycle for electricity and heat production (BIGCC) is particularly interesting because it allows for much higher electrical yield than with conventional combustion with steam cycle.

Several theoretical studies have shown that production based on pressurized gasification of 140-150 MW wood fuel input integrated with a combined cycle could reach a net electrical efficiency of 43-44% by full CHP operation and condensing operation at 46-48%. The overall thermal efficiency is some 86-88%. The fuel dryer is included in the calculations.

At the same time, the development of the conventional cogeneration steam turbine cycle concept has not been standing still. In comparison, a large biomass fuelled CHP plant of 200-300 MWth with steam cycle equipped with re-heat has been reported for a power yield of 32-33% and a total overall net efficiency of 87% without flue gas condensation.

Pressurised gasification with integrated gas and steam turbine cycle was demonstrated in Värnamo in the second half of the 1990s for a number of years based on Foster Wheeler technology. The technology is further described in this report. Moreover, the ARBRE plant which was built in the United Kingdom demonstrated biomass gasification and gas turbine operation but during the commissioning the owner company filed for bankruptcy and the plant was sold. Currently, there is no such similar demonstration or full-scale plant in operation.

It is difficult to analyse and predict for the moment if this technology will be successful in coming years. However, if demonstration- and full-scale plants for biofuels (with pressurized gasification in so-called biorefineries and biomass-to-liquids concepts) will be built, the development of BIGCC will get much help. The basic concept is the same but for BIGCC with a slightly simpler design and gas cleaning comprising cyclones, gas cooling and hot gas filters prior to combustion in the gas turbine. In contrast biorefinery-concepts require additional deep gas cleaning and designs for very high availabilities.

14 Conclusions

There are many ways to utilize biomass as an energy source so many effort is put to develop different efficient technologies. Biomass gasification is one of the thermal biomass conversion processes. It can be used for producing power and heat or for the production of different fuels with higher energy content than biomass. It can provide gaseous and liquid form of fuel that can be used as a substitute for oil derivatives.

Biomass gasification is an emerging commercial technology evolving out of intensive research and development in the 1970s and 1980s, although its developmental roots go back 180 years ago. Despite the fact that there are plenty of gasifiers around the world, most of them are coal based, while the biomass gasification systems from small to large are commercially available only in last 5 years. However a few countries have embraced the demonstration and commercial biomass gasification plants for heat and power generation. Nonetheless, the first large-scale commercial plant for transport fuel production is still not established.

14.1 Background: Pilot and demonstration plant

It is very important to have a verified process in pilot and demonstration scale before commercial application. For large-scale applications like liquid fuels this means many years of costly development without revenues. Projects that have tried to bypass the development steps usually find that costs to adjust in the full-scale plant are much higher and tend to kill the project (e.g. the American company Range Fuels). For one stage applications, pilot testing can be enough of verification of process data for successful scale-up. Examples are the lime kiln CFB's (Ahlström/Foster Wheeler, Götaverken) and the Bioneer fix-bed gasifiers.

The scale-up factor is usually around ten for solid fuel processes. For the back-end processes a higher scale-up factor can be applied in a biomass-to-liquids fuel plant which only operates with gas and liquids. The original CFB gasifiers for lime kilns were also essentially one-step and were scaled up directly from pilot to first commercial size (30 MW_{th} fuel).

14.2 Process complexity

The process complexity can be concluded as in one step or several. The Bioneer gasification technology were well proven commercially already during the 1980s. Extensive pilot testing with a low scale-up factor to commercial size explains the success with several in a few years time. This provides strong evidence that one-step gasifiers without further gas cleaning can be reliable and rather quickly started up even with fully automatic operation.

The later experience with the multistep Novel process with advanced gas cleaning illustrate that this is much more difficult and needs more time and money for commissioning. The automatic operation of gasifiers over long periods of time has been demonstrated only for fixed bed gasifiers (e.g. Bioneer and Babcock & Wilcox). One explanation might be the very slow process in up-draft fixed bed gasifiers in contrast to fluidised-bed and suspension gasifiers. In the Babcock & Wilcox case the automatic operation includes also gas cleaning and engine operation.

The failed demonstrations for waste gasification with gas cleaning serve as a drastic contrast. The Foster Wheeler and Valmet experiences now seem to have reached a good result for waste gasification and cogeneration in coal boilers.

The final commercial step for biomass to liquid fuels still remains to be taken. The reason is that those processes are very large scale and multistep with an uncertain, short-term profitability. The long-term profitability is closely connected to abatement of the climate change effects with a not very clear time perspective.

The efforts to speed up the process e.g. with the NER300 EU projects have had a limited effect as several of the selected have not been able to achieve supplementary private funding. The nearest to commercial operation is Enerkem with a plant in the commissioning phase after both pilot and demonstration operation experience. If successful the commercial prospects seems good as the process is based on waste fuel/RDF. Meanwhile only a few demonstrations for biomass are underway.

14.3 Commercial strength

14.3.1 *Technology development*

The commercial strengths of the developer/contractor and the customer are important to consider. The commercial situation for biomass gasification has been varying over the last 30 years but mostly with a weak market short-term. When small technology developers seek partners for such conditions the strong and profitable companies on related markets usually concentrate on small step development on existing technology e.g. biomass combustion.

The companies prepared to take risk usually have a rapidly weakening existing market and need new products. As the commercial development of biomass gasification have been slow those companies often dies before the new development have resulted commercially.

One early example is **Motala Verkstad** with the Pyrogas waste gasification (with no appropriate pilot experience). Another example is the **TPS/Royal Schelde/KELDA** partnership for the ARBRE BIGCC project in 2002. More examples are **Choren** who faced similar problem with the Beta-plant and became bankrupt in 2011 and **Chemrec**, another small entrained-flow gasification technology company that closed down operations of the DP1 pilot plant when funding became scarce and clients and customers were not there.

Also the early **Güssing** biomass gasification with gas engine project started with bankruptcy of first Austrian Energy and then the second contractor Babcock Borsig Power in 2005. The project was saved by the owners and the Repotec company, which was formed by of the senior technical management involved in the project. Similar development took place in 1996 by the Finnish utility **Tampella** which was bankrupt and the gasification Carbona was formed by the senior management.

Even for strong companies with relatively well proven technology e.g. Foster Wheeler the commercial risk on a weak market can motivate them not to offer the few existing projects. This has recently opened up for new companies in the field such as Valmet (former Metso, Kvaerner and Götaverken) to erect projects for large-scale RDF gasification (Lahti and Vaasa).

The CFB gasifiers starting from the early limekiln gasifiers are the leading type of biomass gasifiers considering the operational experience on biomass as well as other fuels like RDF. The operational problems e.g. sintering have been solved partly with mechanical cleaning and other means when profitable operation conditions have existed. Other companies than Foster Wheeler and Valmet have not generally been as successful with similar technology. This point towards technology development to commercial scale is technology-based only to a minor part.

Commercial strength and partnership are also of major importance. Most technologies have initial problems in the demonstration and commercial scale. Only the partnership or companies that can take the time and cost to sort out the problems can find a long-term success. The cost can be taken by the developer, the construction company or the customer company depending on the strength. If no one has that possibility the development will be stopped with major problems to be restarted.

The Enerkem technology is just now taking the step to commercial scale based on pilot and demonstration experience. The final scale up factor is low about three times. Both these facts led to a rather successful commissioning despite the process consists of a long series of steps. A very strong point is the focus at the profitable short term market for waste gasification.

14.3.2 Differences versus combustion

In a business case comparing combustion with gasification technology it is very difficult to make a detailed analysis of general or specific benefits and disadvantages as there are several, very different reactor technologies in each category (grate, fluidised-bed, shaft, etc) and they depend on fuel, application and possible integration.

Nevertheless, comparing combustion and gasification for a fluidised bed reactor with a moist biomass fuel for combined heat and power production with a steam turbine the gasification technology shows certain significant differences. There is need for a dryer with gasification as waste and biomass in a fluidised-bed reactor requires more fuel pre-treatment than conventional CHP with a boiler. The investment cost and operation and maintenance costs will thus be higher.

On the other hand, low-grade surplus heat may be available for the drying and the energy need will perhaps not be a cost, instead a benefit for an integrated plant. In addition, if the gas is cofired in a boiler the heat exchangers are very expensive and a clean gas may be better for the operation and the maintenance compared with combustion of solid fuels (and the gas boiler could be physically be smaller than a combustion boiler). An investment in a gasifier may also be beneficial as it can be used with existing boilers, instead of an investment in a complete new boiler. Moreover, a filter is usually not needed prior the boiler as the existing plant may already be fitted with sufficient flue gas cleaning.

In general it is difficult to distinguish also differences in process complexity and need for plant operators and the specific maintenance costs as the business cases and technologies vary from project to project. Still it is the assumption that a fluidised bed reactor in principle will not be different for gasification than with combustion regarding these factors.

14.4 Plant availability

The plant operation availability is of great importance for a gasification plant, not only to keep plant economics positive but also for gasification technology as such to compete with other technologies in investments for new production plants. If a gasification process technology has demonstrated lower operation availability than e.g. combustion there may not be commercial possibilities for new investments in this gasification technology, if no improvement can be made in the concept and design.

Plant operation availability may be defined in many different ways. Every production plant has a defined number of equivalent operating hours (e.g. 8000) for a normal year of operation. This is the reference for plant availability and a 100% value equals the same number of equivalent operating hours the plant was operated as the normal operating hours per year.

Another common way of describing the plant availability is the number of operating hours the plant was supposed to operate. The particular operating year may give a number of hours different from the normal year, which normally depend on external factors such as temperature, fluctuating product prices, and internal factors with planned outages. If the plant operated all planned hours (e.g. 5500 hours) the plant availability was 100%. Note the different definition above but the same value.

In some cases the availability may be calculated with reference to the total hours of one calendar year, 8760. This refers to the number of hours the plant was in operation compared with a maximum available hours of possible operation. This is always lower because of planned outages such as regular maintenance and repair, and times when the plant is shutdown during the year for economic reasons such as out of season.

The availability factor should not be confused with the capacity factor. The capacity factor for a period will always be less than the equivalent availability factor for the same period. The difference depends on the utilization of the plant. The net capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity continuously over the same period of time.

The technologies and plants studied have been analysed and some selected plants are given in below Table with the respective plant operating availabilities. A comparison is made with the normal operating hours per year to establish the plant availability for the first 12 months of operation and the total availability to date and the current or recent plant availability. Last the accumulated equivalent operating hours are given.

Tabell 7. Sammanfattning av drifttillgängligheter för valda anläggningar, från Bilaga A.

Table 7. Summary of selected gasification plant operating availabilities, from Appendix A.

Project/plant	Process	Normal	First 12 months	Tot avail.	Current avail.	Accumulated hours
Värö	CFB	8300 h?	No data	No data	No data	>90 000 h
Bioneer	Updraft	8000 h	No data	>99%	>99%	200 000 h on each gasifier
Harboöre	Updraft	8000 h	No data	>95%	97% gasifier, 95% engine	150 000 h gasifier, 65 000 h per engine
Kymenjärvi I	CFB	7000 h	No data	98%	96-99%	27 000 h
Corenso	CFB	No data	No data	90-95%	90-95%	23 000 h (Dec. 2005)
Güssing	FICFB	7500 h	3200 h gasifier, 1300 h engine	>7000 h = 93%	7700 h (2012)	>80 000 h gasifier, >80 000 h engine
Skive	BFB	(+90% for new plant)	(+80% for new plant)	70-80%	80-90%	20 000 h
Oberwart	FICFB	7500 h	1530 h = 20%	82% (goal 86%)	7500 h	26 200 until Dec. 2013
Westbury	BFB	8000 h (design)	No data	No data	95-96%	+5000 h
Varkaus	CFB	4740 h (calc from %)	94.3% gasifier 47.2% slipstream	70% (average)	96% gasifier 93% slipstream	Gasifier 9000 h, Gas cleaning 5500 h
Hortlax	VIPP	8000 h, >85%	<5%, very low	<5%, very low	Reported as good	A few hundred hours
Vaasa	CFB	6500 h	97%, 5000 h (first season)	98%	99%	>9000 h
Gobigas I	FICFB	8000 h	2400 h first 12 months??	No data	No data	>1200 hours (Oct. 2014)

It can be seen that the first 12 months of operation for these plants differs extremely between technologies. For a new technology to be commercially demonstrated (e.g. fluidized-bed with advanced gas cleaning) or a plant with difference in scale, application or integration the availability can be assumed to be very low, most possibly below 40%.

For well-known technologies (e.g. fixed-bed gasifiers with limited cleaning) the availability can be assumed to be very high, approaching 100%, and remain at this level. For the commercial demonstration plants the records have shown several first years of troublesome operation and after a few years the availability has been acceptable in the range of 80-85% and for a couple even >95%.

Thus, all gasification technologies have shown to reach very high numbers given that the lessons are learned and investments are made to correct process difficulties that emanate plant outages. An observation is that most of these selected plants show very high total accumulated operating hours, above 100 000. The conclusion is that there is a great wealth of operating knowledge at these plants which should be considered for a sequential plant of same gasification technology to secure the knowledge transfer.

14.5 Recommendations

The key steps in gasification processes and operational experiences are of great importance. The overall process scheme has to consider redundancy and intermediate storage e.g. after drying and after pressurization of fuel. For multistep processes (including filters) for engines, gas turbines and syngas, the start-up and emergency shutdown sequences are also very important and needs a lot of attention in the engineering phase.

Most gasifiers need a flare for those events and that needs to have a covered (in-built design) not to disturb the surroundings.

Several rather conventional steps are included in most gasification plants. Those parts e.g. wood handling often gets too little attention as focus is on the innovative parts often on gasification and gas cleaning.

Fuel handling, including drying is very important and deserves both high investment cost and skilled suppliers. The problems are small with pellet fuels but increasing with wood chips and especially with low density fuels like straw and RDF (wastes). The fuel systems should have a robust design even if that seems to be costly. Depending on fuel the commissioning of the fuel system can start rather early to avoid interfering with the start-up of the primary gasifiers.

Final feeding and measuring of the fuel flow to the gasifiers are also a source to problems. Usually, measuring and final feeding are separated in two steps. Safety valves to stop gas leaks to the fuel system are important especially at elevated pressure. Most feeding screws operate only with partial fuel filling. Plug screws works if properly designed, but in most cases they are fuel specific.

The gasifiers usually have fewer problems beside the scale-up due to the attention they often get. For difficult fuels sintering have to be considered and can be counteracted with adding steam/water to the gasification air. The pyrolysis part of biomass conversion to gas is limited by heat transfer (particle size) and needs very short residence time at high temperature. The main problem is if the tar content needs to be reduced already in the primary gasifier.

After pyrolysis most biomasses have a residual char of 10-20 weight-%. The most rapid way to convert the char is to burn with the gasification air. Sintering and gasifier design might limit that possibility. For conversion of char with steam the necessary residence time is several minutes at temperatures of 700-900°C. Carbon conversion is therefore a problem in suspension gasifiers and fluidized-beds as the residence time of small particles often are only seconds.

Most gasification plants reported problems with the tar in the gas as in-sufficient gasification operating conditions either yielded higher amounts or improper design of the gas cleaning gave additional problems. This must always be highlighted and proper design may minimize these problems.

Specifically the heat exchangers were reported to be hampered with tar as they gave fouling on the surfaces. They are not only expensive but also important for a high thermal efficiency. One solution offered was to change the more efficient plate fin heat exchanger to tube heat exchangers as they are more robust and the distance between plates may give fouling problems and difficulty to clean afterwards.

The experience of filter operation at normal filter temperature of 150-200°C is generally better than expected. Even reasonably “high” tar content can be accepted. The use of filters means that dust can be handled separately from tar water and that avoids a rather messy sludge handling e.g. in wet filters after the scrubber.

For scrubbers the most successful seems to be organic scrubbing liquid (RME or tar fractions). The spent organic liquid can be fired or recycled to the gasifier. A few water scrubbers also perform well but the spent liquid needs further cleaning before letting out to a public waste water system.

The principle technique to reduce tar in the primary gasifier is to increase the temperature at the exit of the gasifier. This level has to be selected with care because a too high temperature gives more refractory tar and is limited by sintering of the dust. Adding of dolomite or other active substances might have a good effect but problems with clogging of the heat exchanger when cooling have to be solved. In waste or straw gasification limestone or dolomite absorbs chlorine which then can be separated in the filter in dry form.

The other most direct principle is tar reforming catalysts, based on nickel with additions too counteract soot formation which can be used in a monolithic structure on the dust containing raw gas or with a fixed bed catalytic reformer after a high temperature filter. Limited experience exists of both systems, mainly from small scale pilot testing. An exception is Skive where they have, after developing a new hardware system and catalysts, have achieved very good results for tar reforming in commercial operation.

For syngas and reforming of methane a higher temperature and more (weight) active catalyst is needed. The monolithic option then needs several steps and increase of temperature between each step. The fixed-bed option has an advantage but requires pre-filtering with a high temperature filter ($>700^{\circ}\text{C}$) and unfortunately there is today only very limited operational experience. The catalytic solutions give higher total efficiency than scrubbing only. For low-cost and dirty fuels like waste, the scrubbing solution is adequate and the only one close to commercial operation today.

This analysis is based on discussions with plant operators and the learned experience to operate several processes and heterogen fuels at high temperatures and to clean the product gas. There are valuable lessons learned and these recommendations may give considerable cost savings for improved concepts but they also depend heavily on selected technologies with applications and fuel(s).

15 Abbreviations and acronyms

The following abbreviations and acronyms used in the report are here explained.

AGR	Acid Gas Removal
ARBRE	ARable Biomass Renewable Energy
ASU	Air Separation Unit
BED	Burlington Electric Department
BFB	Bubbling Fluidised Bed
BGL	British Gas Lurgi
BIGCC	Biomass Integrated Gasification with Combined Cycle
BIG-GT	Biomass Integrated Gasification – Gas Turbine
BMG	Biomass Gasification
Btu	British Thermal Unit
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
CO	Carbon monoxide
CO ₂	Carbon dioxide
DME	Di-Methyl Ether
DOE	Department of Energy
DRAM	Durability, Reliability, Availability and Maintainability
FICFB	Forced Internal Circulating Fluidised Bed
GT	Gas Turbine
GTI	Gas Technology Institute
H ₂	Hydrogen
H ₂ O	Water
H ₂ O _(g)	Steam
HCN	Hydrogen Cyanide
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
HTW	High Temperature Winkler
IGCC	Integrated Gasification with Combined Cycle
LCV	Low Calorific Value
LHV	Lower Heating Value
MCV	Medium Calorific Value
mg	milligram
MJ	Megajoules (106 joules)
MJ/Nm ³	Megajoule per Normal cubic meter
MSW	Municipal Sewage Waste
MW	Megawatt
MWe	Megawatt electric
MWf	Megawatt fuel input
MWth	Megawatt thermal
NH ₃	Ammonia
NREL	National Renewable Energy Laboratory
PDU	Process Development Unit
ppm	Parts Per Million
SFG	Siemens Fuel Gasification
SNG	Substitute Natural Gas or Synthetic Natural Gas
tDS	tonne Dry Solids
TPD	Tonnes Per Day
TPH	Tonnes Per Hour
TUV	Technical University Vienna
VVBGC	Värnamo Växjö Biomass Gasification Centre
WID	Waste Incineration Directive

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17 Literature references

This project is built on information from the contacted plant owners and the respective process suppliers. Therefore, the specific information for each chapter or technology is referenced to respective company with below internet homepages.

The companies have been able to peer review the respective chapters about the plants and the technologies. The gasification plant data table has been assembled with the information given by these persons and their material as well as public presentations at various conferences like the International Seminar on Gasification by SGC and foremost the Workshops by the IEA Bioenergy Task 33 Biomass Gasification and the Country reports which have given much information.

17.1 Internet

AMEC Foster Wheeler	http://www.fwc.com/
Andritz	www.andritz.fi
Babcock & Wilcox Vølund	http://www.volund.dk/
Bioenergie2020+	http://www.bioenergy2020.eu/
Enerkem	http://www.enerkem.com/en/home.html
Fortum	www.fortum.se
GTC	www.gasification.org/
GTI	www.gastechnology.org/
IEA Bioenergy	www.ieabioenergy.com/
Linde	www.linde.de
Lurgi	www.lurgi.com
Lurgi	www.lurgi.de
Meva Energy	www.mevaenergy.se
Siemens	www.siemens.de
Swedish Energy Agency	www.energimyndigheten.se
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Appendices

- A Gasification plant data table**
- B Table of gasification plant gas compositions**
- C Lurgi**
- D Siemens Fuel Gasification**
- E TPS Termiska Processer**
- F Thyssen Krupp Uhde**

A Gasification plant data table

For higher resolution, see separate electronic file.

Project/plant name, in chronological order	Varo	Bioneer	Harboøre	Värnamo	Kymenjärvi I	Corenso	Güssing	Kokemäki	Skive	Oberwart	Westbury
General											
Location	Varo	Lit, Östersund	Harboøre	Värnamo	Lahti	Varkaus	Güssing	Kokemäki	Skive	Oberwart	Westbury
Country	Sweden	Sweden	Denmark	Sweden	Finland	Finland	Austria	Finland	Denmark	Austria	Canada
Plant owner (current)	Södra Cell Varo	Bygget	Harboøre Värmeværk	VVVG	Lahti Energia	Corenso United	Biomass Power Station Güssing Association Repower TU Vienna	Municipal energy company?	1/5 Skive Fjernvarme	Energie Burgenland	Enertek
Gasification technology	Gittaverken	Rinöner Oy	Babcock & Wilcox Völsund	Foster Wheeler	Foster Wheeler	Foster Wheeler	Repower TU Vienna	Condens Oy	Andritz Carbona	Ormer Anlagensbau	Enertek
Total investment cost	No data	No data	No data	235 mill. SEK	53 mill. SEK Nutek (now Swedish Energy Agency) not including the wood preparation plant.	€11.4 million	€17 million	€9 million	€4.5 million	No data	\$1500-2000/kW
Subsidy						€3 million THERMIE	€3 million (optimization)		+ 12 mill. DKK (Danish Energy Agency) + 12 mill. DKK EU FPS + 11 mill. DKK DOE USA		
Technology											
Units(s)											
Feedstock											
- types	Bark, wood wastes	Wood chips, sawdust, board refuse materials	Wood chips	Wood chips	Wood chips, wood wastes, plastics, demolition wood	Packaging wastes with plastics and aluminium foil	Wood pellets + bark	Waste wood	Wood pellets	Wood chips	Used electricity poles
- moisture content	% (raw -> used)	10%	45-50%	35-50%	45 -> 15%	15-55%	20-40%	45 -> 15%	8-10%	40% -> 15-20%	20-25%
Gasification process	CFB	BIONER	UPDRAFT	BIOFLOW	ACFB	CFB	FICFB	NOVEL	UGAS	FICFB	BIOFIN
reactors / process	1 x CFB	2 x CFB	1 x Updraft	1 x CFB	1 x CFB	1 x CFB (first 8FB)	1 x CFB	1 x Updraft	1 x BFB	1 x FICFB	1 x BFB
- oxidant	media	Air	Air	Air/steam	Air/steam	Air/steam	Heated sand/steam	Air	Air/steam	Heated sand/steam	O ₂ -enriched air/steam
- pressure/temp	bar / °C	Atm. / 800-850	Atm. / 700-900	Atm. / 750-1100	22 / 950-1000	Atm. / 850-1000	Atm. / 600-1000	Atm. / 850	Atm. / 700-850	2 (max 4) / 850-950	Atm. / 850
- carbon conversion	%	No data	No data	No data	No data	99%	No data	No data	No data	No data	>95%
- product gas LHV	MJ/Nm ³	7	No data	5.6	5.3-6.3	2.2 MJ/kg	No data	12-13	No data	5.5	No data
Gas cleaning											
- tar removal/reforming	process	No	No	Electro-static	Hot gas cleanup	No	No	EMF scrubber	Nil monolith	Nil monolith	EMF scrubber
- other	process	N/A	N/A	Tar and water cleaning system (Tar/Wat)	Scrubber	N/A	N/A	Acid/base scrubber	N/A	Water scrubber	Tar/water to gasifier, Acid
- gas filter	type	N/A	Baghouse?	Electro-static	Ceramic + metal	Ceramic	Baghouse?	Baghouse	Ceramic	Baghouse	Baghouse
- gas filter temp.	°C	N/A	No data	35	No data	320-350	No data	150	150-200	200	150
Gas application											
- co-combustion	yes/no	Yes, lime kiln	Yes, boiler	No	Yes, boiler	No	Yes, boiler	No	Yes, 2 x 10 MW boiler	No	No
- engine/turbines (gas-steam)	model	N/A	N/A	JMS 920 GS Jenbacher	EGT Typhoon nadrowski ST	N/A	N/A	JMS 620 GS Jenbacher	JMS 616 GE Jenbacher	JMS 620 GS Jenbacher	JMS 612 GS Jenbacher
- number and capacity	number x ? MW	N/A	N/A	2 (648 + 761) kW	1 x 4.5 + 1 x 1.5 MW	N/A	N/A	1 x 2 MW	3 x 600 kW	3 x 2 MW	2 x 1.2 MW
- ORC-process	MW	No	No	No	No	No	No	No	No	No	0.35 MW
Balance											
Units(s)											
Consumption											
- feedstock	MWth	30-35	4 + 6	5	18	40-70	40 (increased to 50)	8	6.1 (incl boiler 7.2)	8.5	5-8
- feedstock	t/d or t/a	No data	No data	35 t/d or 16 000 t/a	100 t/d	100 000 t/a	82 t/d (as dry) 27 000 t/a	2.2 t/h or 50 t/d	7.2 t/d	23 000 t/a or 60 t/d	12 000 t/a or 30 t/d (as dry)
Production											
- power	MWth	N/A	N/A	1	6	7-23 (18 typical)	13	2	1.4	5.6	No data
- heat	MWth	No data	No data	3.5	9	Co-fired and together with CHP plant	20 MW (not confirmed)	4.5	3.1 (incl boiler 4.3)	11.3	4.1
- gas / synthesis products	Unit	N/A	N/A	N/A	N/A	48 000 Nm ³ /hr	N/A	N/A	N/A	N/A	Max capacity 4000 m ³ ethanol/s
Performance											
Units(s)											
Efficiency to power/syn-product	LHV %	N/A	N/A	28%	33%	33%	26%	25%	30-36%	28%	33%
Efficiency total, thermal	LHV %	No data	No data	34%	37%	38%	36%	30%	30%	37%	38% (estimated)
Operation, normal	hours/year	No data	8000 h	8000 h	7000 h	7000 h	No data	7500 h	No data	(+90% for new plant)	7500 h
Availability, 1 st year (or season)	%	No data	No data	No data	1300 h	No data	No data	3200 h gasifier = 43% 1300 h engine	No data	(+80% for new plant)	1530 h = 20%
Availability, total	%	No data	>99%	>95%	No data	98%	90-95%	>7000 h = 95%	No data	70-80%	82% (low 86%)
Availability, last Q or trend	%	No data	>99%	97% gasifier 95% engine	No data	96-99%	90-95%	7700 h (2012)	No data	7500 h	95-96%
Emissions											
- NOx @ 11% O ₂	mg/Nm ³	No data	No data	400 @ 5% O ₂	50-150	(limit 230 mg/MJ)	No data	<500 @ 5% O ₂	No data	No data	168 (limit 650)
- CO @ 11% O ₂	mg/Nm ³	No data	No data	1125 @ 15% O ₂ 1500 @ 5% O ₂	<200 and 0-4 ppm HC	No data	No data	<3000 (w/o catalyst) <650 (with catalyst)	No data	low w/o catalyst (below limit)	22 (limit 500)
- Particulates, dust	mg/Nm ³	No data	47 (limit 100)	<25	5 (limit 35)	No data	No data	<20 @ 5% O ₂	<10	No data	<5
Status											
Construction period	date	No data	1986 - 1987	No data	No data	No data	2000 - 2001	Sept 2000 - ???	May 2004 - April 2005	April 2005 - Aug 2006	Aug 2006 - Dec 2007
Startup, gasifier	date	1987	1987	1993 (optimization to 1996)	June 1993	1997	2001	April 2005	Aug 2006	Aug 2006	Dec 2007 first start
In full operation	date	1987-1991, 2003-2014	1987 - 2013	1996 - , 2003 -	1996 - 1999	1998 - 2002	2001 -	Jan 2002 - >	2006 - 2009	June 2007 - >	Aug 2010 start of normal operation
Accumulated hours		>80 000 h	200 000 h on each gasifier	150 000 h gasifier 65 000 h per engine	8500 h gasifier 3600 h gas turbine	27 000 h	23 000 h (Dec 2005)	>80 000 h gasifier	No data	20 000 h	26 200 until Dec 2013
Comments		Not operating early 1990s. Rebuilt 2008, stopped in April 2014.	Running continuously since start. Closed April 2013 for 4 MW and June for 6 MW.	Rebuilt to CHP in 2003 with gas cleaning and engines and accumulator tank. Stable operation from 2003, >95 % avail.	Mothballed 2000.	Closed, operating occasionally after 2002. Accumulated fuel 400 000 tonnes.	Rebuilt to 15 MW BFB pilot in 1997 which operated 1400 h. Recycling of aluminium from wastes.	Campaign operation. Company became insolvent in 2013, plant stop July-Oct 2013.	Closed. 1st engine startup in winter 2005, 2nd and 3rd engines winter 2006.	In operation.	First year demanded a re-start with optimization. Oct 2013 change of refractory riser.

N/A = Not applicable

Gasification plant data table (continued)

Project/plant name, in chronological order	Chicago	Villach	Varkaus	Senden/Ulm	Kymenjärvi II	Hortlax	Vaasa	Edmonton	Joutseno	Göteborg	Pontotoc
General											
Location	Chicago, Illinois	Villach	Varkaus	Senden/Ulm	Lahti	Hortlax, Piteå	Vaasa	Alberta	Joutseno	Göteborg	Pontotoc, Mississippi
Country	USA	Germany	Finland	Germany	Finland	Sweden	Finland	Canada	Finland	Sweden	USA
Plant owner (current)	GTI	Biomasse-Energie GmbH	NSE Biofuels	Stadtwerke Ulm/Neu-Ulm GmbH	Lahti Energia	Pite Energi	Vaskiluodon Voima	Enerkem	Metsä Fibre	Gothenburg Energy	Enerkem
Gasification technology	Andritz Carbona	Ortner Anlagenbau	Foster Wheeler	Repotec	Valmet (Metsä)	Meva Energy	Valmet (Metsä)	Enerkem	Andritz Carbona	Repotec / Metsä	Enerkem
Total investment cost	Gasoline project: \$35 million. Subsidy: \$25 million DOE	No data	€14 million	No data	€160 million	40 million SEK 2.5 mill. SEK Swedish Energy Agency 2.5 mill. SEK Vinnova	<€40 million €10.8 million Finnish Ministry of Employment	CAS100 million CAS20 million grant	No data	1800 million SEK 222 million SEK Swedish Energy Agency	\$100 million \$50 million DOE
Technology											
Units(s)											
Feedstock											
- types	Wood pellets, but tested for wood chips, bark, residues	Wood chips	Wood chips, bark, sawdust, forest residues	Wood chips	Demolition wood, household wastes, plastics, SRF	Wood pellets ground to 6-8 mm particles	Wood chips, straw, reed canary grass, peat	Sorted MSW	Pine, spruce, and birch bark	Wood pellets	Sorted MSW
- moisture content	% (raw -> used)	No data	50 -> 30-20%	45%	45 -> 20%	No data	No data	20-25%	50% ->15%	8-10%	20-25%
Gasification process											
- reactors / process	1 x type	UGAS	FICFB	CFB	FICFB	ACFB	VIPP	BIOSYN	CFB	FICFB	BIOSYN
- oxidant	media	1 x BFB	1 x FICFB	1 x CFB	1 x FICFB	2 x CFB	1 x CFB	1 x CFB	1 x BFB	1 x CFB	1 x BFB
- pressure/temp	bar / °C	Oxygen/steam	Heated sand/steam	45% oxygen/steam	Heated sand/steam	Air/steam	Air	O ₂ -enriched air/steam	Air/steam	Heated sand/steam	O ₂ -enriched air/steam
- carbon conversion	%	28 / 950	Atm. / 850	Atm. / 870-890	Atm. / 850	Atm. / no data	1,3 bar / 850-900	Atm. / 750-900	<3 / 700-750	Atm. / 750-800	<3 / 700-750
- product gas LHV	MJ/Nm ³	>99%	No data	+99%	No data	No data	96%	No data	>95%	No data	>95%
Gas cleaning											
- tar removal/reforming	process	Ni monolith	RME scrubber	Catalytic reformer	RME scrubber	No	RME scrubber	No	Water scrubber	No	RME scrubber
- other	process	Morphysorb + Sulfatreat	No data	Scrubber + Acid Gas Removal	No data	No data	N/A	N/A	Tar/water to gasifier, Acid Gas Removal unit	No	Tar/water to gasifier, Acid Gas Removal unit
- gas filter	type	No data	No data	Two gas filters	No data	No data	Wet electrostatic precipitator (WESP)	No data	Baghouse	No data	Baghouse
- gas filter temp.	°C	No data	No data	550-570	No data	No data	No data	N/A	150	No data	No data
Gas application											
- co-combustion	yes/no	No	No	Yes, lime kiln	No	Yes, boiler	No	Yes	No	Yes, lime kiln	No
- engine/turbines (gas+steam)	model	N/A	JMS 620 GS Jenbacher	N/A	JMS 620 GS Jenbacher	N/A	Cummins QSV91	N/A	N/A	N/A	N/A
- number and capacity	number x ? MW	N/A	2 x 2 MW	N/A	2 x 2 MW	N/A	1 x 1,2 MW	N/A	N/A	N/A	N/A
- ORC-process	MW	No	No	No	0,6 MW	No	No	No	No	No	No
Balances											
Units(s)											
Consumption											
- feedstock	MWth	Nominal 5, range 4-8	15	12	14,5	160	4,5	140	35	48	32
- feedstock	t/d or t/a	24 t/d (with air), 40 t/d (with O ₂)	33 000 t/a	60 t/d (as dry)	45 000 t/a	250 000 t/a	960 kg/h 7500 t/a	800 t/d	>100 000 t/a, 228 t/d (as dry)	528 t/d, 175 000 t/a	+ 0,5 MW RME
Production											
- power	MWe	N/A	3,9	N/A	4,6	50	1,3	43	No data	N/A	-3 (import)
- heat	MWth	N/A	6,7	N/A	6,4	90	2,2	Co-fired with coal	No data	No data	11 (incl 6 MW heat pumps)
- gas / synthesis products	Unit	Methanol to 23 BPD gasoline or 3660 liter/day	N/A	Slip-stream tested for FT-production (0.1 MW)	N/A	112 000 Nm ³ /hr	N/A	N/A	Max 38 000 m ³ ethanol/a	N/A	20 MW SNG
Performance											
Units(s)											
Efficiency to power/syn-product	LHV %	N/A	26%	50-55% to FT	32%	31%	29%	31%	No data	N/A	65%
Efficiency total, thermal	LHV %	N/A	63%	80% with r-i-concept	80%	88%	/8%	Lo-fired with coal	No data	No data	90% (import power to heat pumps, not incl.)
Operation, normal	hours/year	Campaign operation	No data	4740 h (calc. from %)	7000-7200 h	No data	8000 h, >85%	6500 h	90% uptime	No data	8000 h (90% uptime goal)
Availability, 1 st year (or season)	%	No data	No data	94.3% O ₂ /H ₂ O gasifier	No data	No data	Very low, est. <5%	97%, 5000 h (first season)	(+73% goal)	No data	2400 h first 12 months?? (estimated)
Availability, total	%	No data	No data	70% (average)	No data	No data	Very low, est. <5%	98%	(+91% goal)	No data	No data
Availability, last Q or trend	%	No data	No data	96% O ₂ /H ₂ O gasifier	93% slipstream	No data	Reported as good	99%	(+90-95% goal)	No data	No data
Emissions											
- NOx @ 11% O ₂	mg/Nm ³	N/A	No data	N/A (no data from kiln)	No data	(limit 240)	No data	350 (limit 500)	94 (when combusted)	No data	No data
- CO @ 11% O ₂	mg/Nm ³	N/A	No data	N/A (no data from kiln)	No data	No data	No data	No data	0.4 (when combusted)	No data	No data
- Particulates, dust	mg/Nm ³	N/A	No data	N/A (no data from kiln)	<5	10-20	No data	No data	4.8 (when combusted)	No data	No data
Status											
Construction period	date	2009	2009 - 2010	June 2008 - 2009	Dec 2009 - Dec 2011	No data	May(?) 2010 - Okt 2011	May 2012 - Oct 2012	June 2010 - Dec 2013	Sept 2012	Oct 2011 - Oct 2013
Startup, gasifier	date	2009 Gasifier Aug 2012 w TIGAS	2010	June 2009	Dec 2011	Jan 2012	May 2012	Oct 2012	Dec 2013	2014	2017??
In full operation	date	2009 -> 800 h, 8000 gallons gasoline to 2010	No data	June 2009 - June 2011	No data	April 2012	2014?	Dec 2012 -> >17 000 h	June 2014 -> 6 months	No data	June 2014 -> >1200 h (Oct 2014)
Accumulated hours		800 h, 8000 gallons gasoline to 2010	No data	Gasifier 9000 h Gas cleaning 5500 h	No data	>17 000 h	A few hundred hours	>9000 h	No data	No data	0
Comments		Campaign operation.	Troublesome startup. The plant company became bankrupt by spring 2013.	Closed.	Three years of bad startup.	In operation, troublesome first years.	Very troublesome operation. Delayed two years. In operation, redesign 2014 tar removal.	Very high availability.	The oxidant will first be air, then air/oxygen and last oxygen/steam. In 2015 an ethanol step will be added for production in 2016.	In operation.	In operation with gas to grid Oct 2014.

B Table of gasification plant gas compositions

Plant	Skive		Harboöre		Kymenjärvi I	Kymenjärvi II	Güssing		Oberwart	Hortlax		Värö	
Feedstock	Pellets		Wood chips		Wood wastes	Wood wastes	Pellets		Wood chips	Pellets		Bark, wood	
Outlet gas	Raw	Cleaned	Raw	Cleaned	Raw	Raw	Raw	Cleaned	Raw	Raw [$\lambda = 0.29$]	Cleaned	Typical	Design
H ₂	20.7%	15.5%	19.0%	15-20%	9.3%	6-9%	31.5%	35-45%	35-42%	9.6%	8.5%	14.2%	10.3%
CO	23.4%	18.2%	22.8%	25-30%	7.2%	7-10%	22.7%	22-25%	18-23%	20.4%	21.0%	19.9%	15.1%
CO ₂	9.9%	13.9%	11.9%	7-10%	20.3%	13-16%	27.4%	20-25%	20-24%	12.6%	13.0%	14.2%	15.9%
CH ₄	0.9%	5.5%	5.5%	3-6%	3.4%	4-6%	11.2%	<10%	7-10%	4.0%	4.0%	6.3%	5.1%
C ₂ H ₄ + C ₂ H ₆ + C ₂ H ₂	as BTX	160 ppm(v)	<25 mg/Nm ³	N.D.	N.D.	2-3%	4.0%	3-4%	3-4%	2.1%	N.D.	N.D.	2.1%
BTX (mostly C ₆ H ₆) + C ₇₊	20 ppm(v)	0.15%	80 g/Nm ³	N.D.	as CH ₄	10-20 mg/Nm ³	N.D.	10 g/Nm ³	10 g/Nm ³	0.2%	N.D.	N.D.	N.D.
H ₂ S	80 ppm(v)	80 ppm(v)	N.D.	N.D.	N.D.	N.D.	N.D.	100 ppm(v)	100 ppm(v)	4 ppm(v)	4 ppm(v)	N.D.	N.D.
COS	as H ₂ S	as H ₂ S	N.D.	N.D.	N.D.	N.D.	N.D.	30 ppm(v)	30 ppm(v)	0.2 ppm(v)	0.2 ppm(v)	N.D.	N.D.
N ₂	41.7%	44.0%	40.7%	40.0%	60.0%	55-60%	2.8%	1-3%	1-3%	49.6%	50.0%	45.5%	43.5%
NH ₃	50 ppm(v)	500 ppm(v)	N.D.	N.D.	N.D.	N.D.	N.D.	500-1000 ppm(v)	500-1000 ppm(v)	<10 mg/Nm ³	<10 mg/Nm ³	N.D.	N.D.
HCN	as NH ₃	as NH ₃	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
HCl+Br+F (halides)	30 ppm(v)	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	3 ppm(v)	3 ppm(v)	<10 mg/Nm ³	<10 mg/Nm ³	N.D.	N.D.
Na+K (alkali)	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	<1 mg/Nm ³	<1 mg/Nm ³	N.D.	N.D.
H ₂ O (value as separate)	3.3%	2.7%	N.D.	N.D.	Dry basis	(20-30%)	Dry basis	Dry basis	Dry basis	Dry basis	Dry basis	(11.5%)	7.9%
Gas sum	99.9%	99.9%	99.9%	100.0%	100.2%	100.0%	99.6%	100.0%	100.0%	98.5%	96.5%	100.0%	99.9%
LHV, MJ/Nm³	5.5	4.8-5.2	5.6	N.D.	2-2.5	N.D.	N.D.	N.D.	N.D.	6.6-6.8	6.6-6.8	7.0%	7.0%
LHV, MJ/kg	10.6	N.D.	12.3	N.D.	5.1	N.D.	N.D.	12-13	12-13	N.D.	N.D.	10.7	10.7

N.D. = No Data

Table of gasification plant gas compositions (continued)

Plant	Gobigas I	Westbury	Edmonton	Pontotoc	Varkaus	Villach	Vaasa	Värnamo	Kokemäki	Bioneer	Chicago	
Feedstock	Pellets	Used tree poles	MSW	MSW	Wood chips	Wood chips	Wood wastes	Pellets, wood	Waste wood	Wood wastes	Wood chips	
Outlet gas	General	1)	2)	3)	Raw	Typical	Typical	General	Typical	Typical	Raw	Cleaned
H ₂	38-45%	6-12%	20-24%	50-60%	21.0%	45.0%	9-11%	10-12%	N.D.	11.0%	29.0%	42.0%
CO	22-25%	14-15%	20-24%	25-30%	17.0%	21.0%	12-15%	15.5-17.5%	N.D.	30.0%	27.0%	37.0%
CO ₂	20-23%	16-17%	30-35%	<5%	21.0%	25.0%	15-17%	14-17%	N.D.	7.0%	17.0%	19.0%
CH ₄	9-12%	3-4%	8-12%	<4%	6.2%	9.0%	4-6%	5-7%	N.D.	3.0%	3.8%	0.8%
C ₂ H ₄ + C ₂ H ₆ + C ₂ H ₂	1.0%	2.9-4.1%	8-16%	<2%	1.9%	N.D.	2-3%	N.D.	N.D.	N.D.	0.10%	<200 ppm(v)
BTX (mostly C ₆ H ₆) +C ₇₊	2.3 g/Nm ³	N.D.	2-4%	Trace	35 g/Nm ³	10 g/Nm ³	20-30 mg/Nm ³	<5 g/Nm ³	1-4 g/Nm ³	50-100 g/Nm ³	0.23%	<100 ppm(v)
H ₂ S	40-70 ppm(v)	N.D.	N.D.	<20 mg/Nm ³	N.D.	N.D.	N.D.	N.D.	<100 mg/Nm ³	N.D.	50 ppm(v)	50 ppm(v)
COS	30 ppm(v)	N.D.	N.D.	in H ₂ S	N.D.	N.D.	N.D.	N.D.	<10 mg/Nm ³	N.D.	50 ppm(v)	50 ppm(v)
N ₂	2-3%	36-58%	<5%	<5%	0.7%	N.D.	40-55%	45-50%	N.D.	49.0%	0.08%	0.18%
NH ₃	1000-2000 ppm(v)	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	380-1900 ppm(v)	10 mg/Nm ³	N.D.	0.13%	<10 ppm(v)
HCN	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	0-4 ppm(v)	As NH ₃	N.D.	As NH ₃	As NH ₃
HCl+Br+F (halides)	N.D.	N.D.	N.D.	<5 mg/Nm ³	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	As NH ₃	None
Na+K (alkali)	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	None
H ₂ O (value as separate)	Dry basis	Dry basis	Dry basis	Dry basis	31.0%	Dry basis	(25-30%)	Dry basis	N.D.	N.D.	0.23%	0.74%
Gas sum	100.0%	100.0%	100.0%	100.0%	98.8%	100.0%	100.0%	100.0%	N.D.	100.0%	100.0%	99.7%
LHV, MJ/Nm ³	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	5.3-6.3	N.D.	6.2	N.D.	N.D.
LHV, MJ/kg	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Gasification mode: 1) Air/enriched-air gasification, 2) O₂/steam gasification, 3) O₂/steam gasification + steam reforming and CO₂ removal.

C Lurgi

C.1 Background

Lurgi is a leading international technology company operating in the field of process engineering and plant contracting. Lurgi's parent company, Paris-based Air Liquide Group, is an international producer of medical and industrial gases with some 37 000 employees in 72 countries.

Lurgi possesses technologies and expertise for fuel production in a Biorefinery, where they have developed both gas cleaning (e.g. Rectisol) and methanol synthesis, where they are the market leader in cooperation with Linde who also offers the Rectisol technology. In Sweden they are represented by Christian Berner, which is one of the biggest company groups within technology agent trading in the Nordic countries. They deliver technical equipment, components and materials.

C.2 Technology

Part of the development started like the previous gasification company Choren with the Deutsche Brennstoff Institut and Lurgi has for many years developed predominantly solid fossil fuel gasification with fixed bed gasification and has successfully delivered a large number of plants, e.g. 80 coal gasifiers in South Africa.

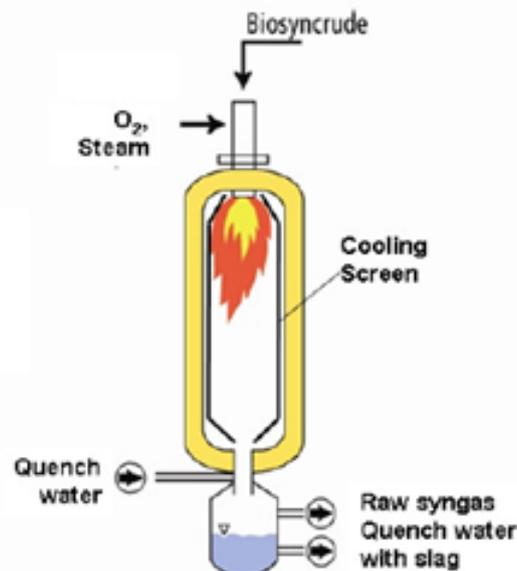


Figure 87. Schematic of MPG gasification reactor (Ref. Lurgi).

Subsequently, a CFB gasifier was developed for different fuels and later a Multi-Purpose-Gasification (MPG) process, acquired from SVZ Schwarze Pumpe (1998) which essentially is entrained-flow brick-lined oxygen-blown, water quench gasifier for liquid fuels. Lurgi has made further development of the process and tested it with pyrolysis products.

The test program was reported to be finalised in one year and scheduled to be ready for commercial offers in 2014. Lurgi has developed the Bioliq-Process, which is a joint development with FZK in Karlsruhe where they have tested pyrolysis of agricultural residues which then have been transported to Lurgi for tests in the MPG gasifier, situated in Freiberg.

The MPG process is centred on an entrained-flow reactor able with cooling screen to operate at temperatures of 1200-1400°C and at high pressure. It is commercially proven for refinery residues and is developed now for integration with a coker for gasification of a biosyncrude.

C.3 Operating experience

Lurgi has an engineering group and gasification centre in Freiberg, Germany where the HP POX pilot plants demonstrate production of syngas from natural gas, liquid hydrocarbons/slurries at pressures up to 100 bar. The plant is no longer in operation.



Figure 88. Photograph of the 2 MWf pilot plant (Ref. Lurgi).

The pilot plant with a capacity of 500 kg/hr liquid feedstock started in June 2004 and they have reported more than 1000 hours of smooth operation. A gasification pressure of 70 bar has been proven.

D Siemens Fuel Gasification

D.1 Background

Siemens Fuel Gasification is located in Freiberg and has many years of extensive experience in predominantly fossil fuels. There are two pilot plants of 3 and 5 MW capacity, respectively. However, the former East-German company Noell-KRC Umwelt- und Energietechnik originally developed high temperature entrained flow gasification technology, which demonstrated a slagging gasifier at SVZ plant in Schwarze Pumpe. After the German reunification in 1990 the company was merged to Preussag Noell in 1998, and then sold to Babcock Borsig, which after a bankruptcy reconstructed as Future Energy and eventually being bought by Siemens in 2006.

The development started with the Deutsche Brennstoff Institut and the GSP (Gaskombinat Schwarze Pumpe) process which features high pressure oxygen blown, entrained flow gasification for solid or liquid fuels. The first commercial development was the GSP plant at the Schwarze Pumpe complex with 130 MWth liquid wastes (tar, oil, solvents, waste oils, emulsions) gasified at 24-30 bar, 1700°C for synthesis gas production and 120 000 tonnes/year methanol synthesis as well as PG6B 45 MWe gas turbine. This plant tested many types of fuels but little experience have been made into biomass. Below is given a summary of the total development.

Year	Fixed-bed gasification	
1956 1977	24 gasifiers constructed in the gas combine „Schwarze Pumpe“	
	DBI	
	Entrained-flow gasification	
	Demonstrations plants Freiberg	Commercial plants
1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989	Lignite Saliferous lignite 42 lignite varieties 15 hard coal varieties (international) Pulverized hard coal and lignite Petcoke, flue ash 3 MW	Lignite Saliferous lignite Natural gas Waste oil, tar oil Slurry Tar oil/solid sludges 200 MW Schwarze Pumpe
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999	15 municipal and industrial sewage sludges, MSW, waste oil, wood, straw Slurry, flue ash Industrial waste and residues 5 MW Chlorinated organics Nitrogen waste organics Black liquor	Nitrogen waste organics 13 t/h Seal Sands
2000 2001 2002	Bioslurry, coal Hard coal	Tar oil Babcock
2003 2004 2005 2006 2007 2008	Hard coal	Hard coal Vřesová FUTURE ENERGY Anhui Huainan Project NingMei DME Project

Figure 89. Summary of the gasification development at Freiberg by Siemens.

D.2 Technology

The SFG process is centred on an entrained-flow reactor able to operate at temperatures of 1200-1400°C and at 5-25 bar (for wood pyrolysis), with an outlook of going to 50 bar. Solids are pneumatically fed to the gasifier however in this case for biomass pyrolysis liquids are pumped. The process therefore is primarily suited for biomass liquids. However, there is a new interesting possibility with torrefaction.

Torrefied wood is made by a mild pyrolysis of biomass at temperatures of 240-280°C for duration of 1 to 3 hours, named torrefaction. Torrefaction gives a carbon similar to coal with a stable moisture content of about 3%, reduction of mass by 30% compared to the raw material, retention of 90% of original energy content and removal of smoke producing agents. Thus, the fuel can be used with dry feeding much in the same way as have been used for coal.

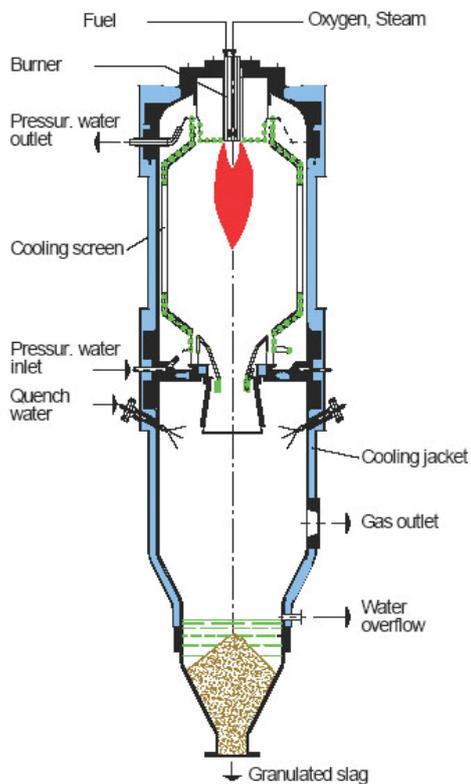


Figure 90. Schematic of SFG gasification reactor and photograph of the 3 MWf pilot plant showing bottom sections with water quench and slag removal (Ref. Siemens).

The Siemens technology has been tested with different feed systems like dry lock hoppers and slurry feed. The preferred design for coal is dry lock-hoppers. The lock hopper design in different gasifiers, is similar in that both achieve a good degree of filling and a minimum of feed gas consumption.

Siemens has an engineering group and gasification centre in Freiberg, Germany and also people in Beijing supporting the joint venture. Siemens Gasification Group's recent focus has been on the use of coal for production of synfuel, methanol and ammonia.

Currently, BioMCN develops a project together with NOM, Linde, Visser & Smit Hanab incorporating Siemens technology. BioMCN has formed a consortium to build a large scale biomass refinery next to the existing BioMCN plant in Delfzijl. The project will use sustainable cellulosic material such as waste wood as raw material and produce 400 000 ton methanol per year. The NER 300 grant award is 199 MEUR.

E TPS Termiska Processer

This text chapter is in full extracted from the IEA Bioenergy Task 33 Annex 1 to the IEA Biomass Agreement Task 33, Country report Sweden 2012 by Lars Waldheim of Waldheim Consulting AB published in May 2012.

E.1 Background

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 Swedish Energy Agency, 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 MWf 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 MWf 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/m³ 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.

E.2 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 below)
2. Firing of the gas in a gas engine / dual-fuel engine
3. Firing of the gas in an IGCC system (Figure next page).

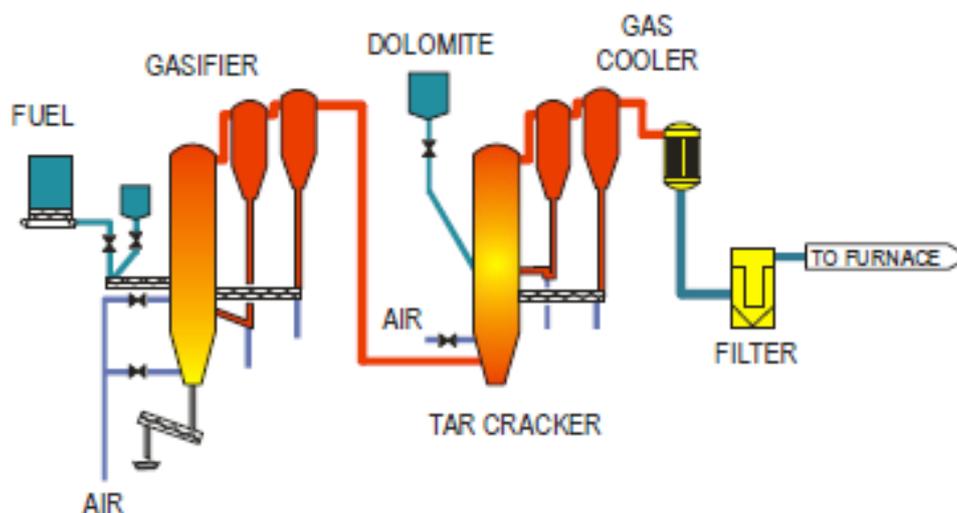


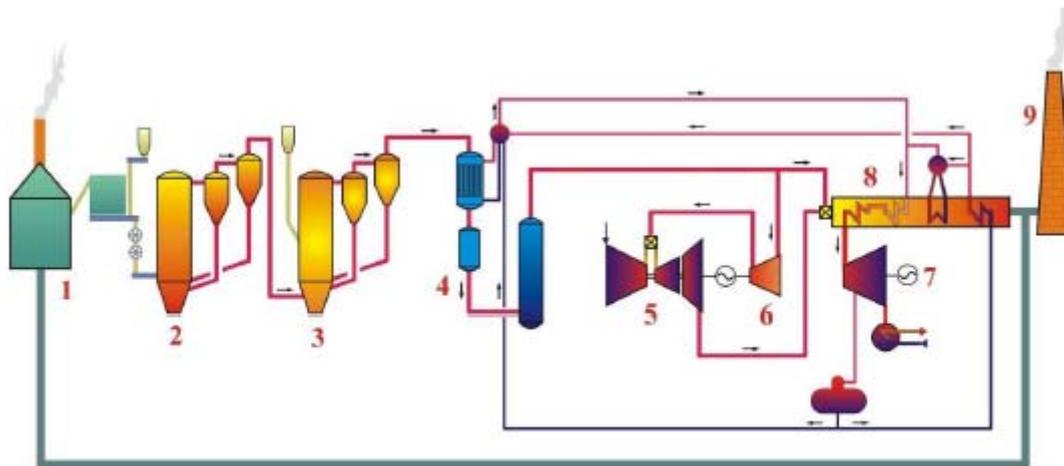
Figure 91. Gasification for co-firing in a boiler.

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 MWf 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 MWe 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 dualfuel 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).



1 Dryer, 2 Gasifier, 3 Tar Cracker, 4 Cooler, Filter, Scrubber, 5 Gas Turbine Generator
6 Gas Compressor, 7 Steam Turbine, 8 Heat Recovery Steam Generator, 9 Stack

Figure 92. 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.

E.3 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.

E.4 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 byproduct 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.

E.5 Project ARBRE

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. The Figure below shows a simplified process flow diagram of the plant.

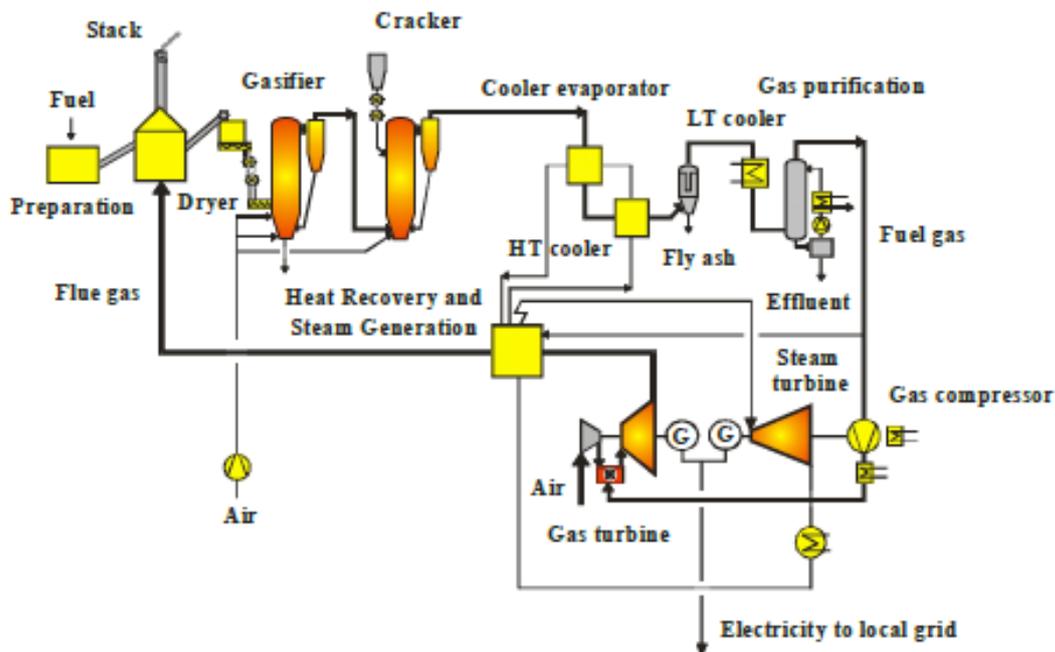


Figure 93. ARBRE plant process scheme.

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 MWe 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 subcontract with TPS. The plant's O&M contract was awarded by AEL to Schelde Heat and Power (SHP) UK Limited.

E.5.1 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.

E.5.2 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 CaCl₂). 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.

E.5.3 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 MWe. 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 MWe steam turbine. The steam leaving the steam turbine is condensed in a hybrid cooling plant and returned to the boiler.

E.5.4 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 subcontractors. The Figure below shows the ARBRE plant in June 2001.



Figure 94. The ARBRE plant in June 2001.

E.5.5 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 1000 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.

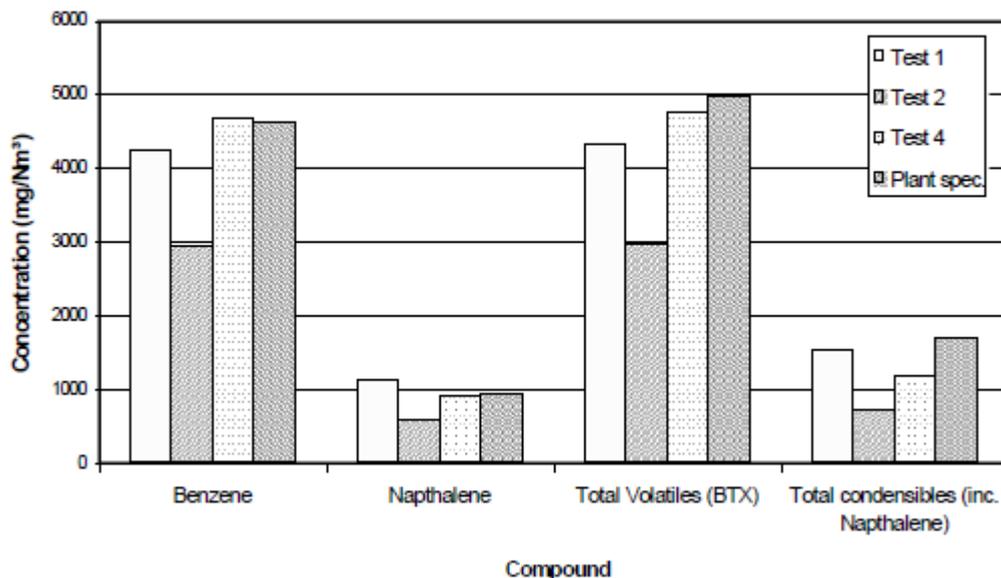


Figure 95. Tar levels in fuel gas.

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 CaCO₃, 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 MWe. 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

E.5.6 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

E.5.7 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 non-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 Swedish Energy Agency 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.

F Thyssen Krupp Uhde

F.1 Background

Uhde is a large engineering contractor firm situated with head office in Dortmund and part of Thyssen Krupp providing process engineering to the international plant construction industry. The company can offer whole technology lines by partnership with other companies focusing mainly regarding energy the natural gas, coal and petrochemical industry.

As a technology-oriented company, Uhde has extensive experience in the development, design and construction of oil and coal conversion plants. This experience dates back about 65 years. To date Uhde has designed and constructed more than 100 gasifiers around the world based on eight different gasification technologies catering for all types of feedstock – solid, liquid and gaseous.

These include the Koppers-Totzek coal gasification process, the Texaco Gasification Process for liquid feedstocks, and solid (hard coal with medium ash content), and gaseous and the Shell-Koppers Gasification Process for solid feedstocks, such as hard coal, petroleum coke (a joint development with Shell). For biomass, Uhde is the owner of the High Temperature Winkler (HTW) fluidised bed gasification process, particularly designed for low-rank feedstocks, such as coal, lignite, biomass and also plastics.

F.2 Development

The original HTW process was invented by Rheinbraun AG and was used for many years in pilot and demonstration plants to generate synthesis gas and fuel gas out of brown coal.

Uhde has accumulated extensive experience from several gasification technologies, predominantly with fossil fuels, and acquired several companies related to gasification. For example, Uhde has a long cooperation with Shell for both coal and oil fuels, where Uhde built the Buggenum plant in Holland with the Shell Coal Gasification Process – a joint development by Uhde and Shell in the 1970s. Another example is the Koppers-Totzek Gasification Process (KTP) via Krupp Koppers who merged with Uhde in 1997. A total of 77 KTP units were designed and constructed by Uhde over the last 60 years.

Uhde has also operated a demonstration plant, equipped with a pressurised entrained-flow gasifier (PRENFLO), in Fürstenhausen, Germany with a capacity of 48 TPD. The results and experience have been used for the successful design of Elcogas' 2400 TPD, 335 MWe coal IGCC power plant in Puertollano, Spain

The HTW process is a development of the old Winkler fluidised bed gasification process, first developed and used in the 1920s and was an atmospheric-pressure process. The HTW process was originally developed to produce reducing gas for iron ore; interest then switched to the production of synthesis gas, then to power generation. All these applications were based on the gasification of lignite and there are 40 plants being built.

At the time Rheinbraun was responsible for the development of the HTW process, with Krupp Uhde undertaking the marketing and supply. Rheinbraun built a pilot plant at Frechen, which ran from 1978 to 1995. It was rated at 10 bar and 1.8 tonnes per hour.

In 1985 a demonstration unit was built at Berrenrath near Cologne. This ran at 10 bar, the syngas produced being piped to a methanol synthesis plant at nearby Wesseling. The 160 MWf Berrenrath plant used steam and oxygen as the gasification media and accumulated 67 000 hours of operation with 792 000 tonnes methanol produced at an availability of 85% on average.



Figure 96. Photograph of Rheinbraun's Berrenrath plant (Ref. Uhde).

In 1989 a 25 bar pilot plant was started at Wesseling with the intention of developing the process for power generation from lignite. The work culminated in the design of an IGCC based around an air-blown HTW gasifier and termed KOBRA (Kombikraftwerk mit Integriertier BRAunkohlvergasung - combined cycle with lignite gasification).

The initial KoBRA plant was due to be built at the Goldenberg power station near Cologne; however, economic considerations intervened and the project was dropped. RWE launched a 450 MWe IGCC project for 2014 but the project was cancelled.

Following the demise of the KoBRA IGCC project, the emphasis switched to the gasification of wastes and biomass. Tests were carried out at the Berrenrath plant to investigate the gasification of waste plastics and operational experience was also made with peat and wood (co-gasification) as was demonstrated in late 1980s at 120 MWf Oulu Kemira ammonia plant in Finland. This plant was however operated with oxygen and the total experience with wood was limited. The plant was shut down soon thereafter due to falling world prices of ammonia.

F.3 Technology

The HTW process takes place in a fluidised bed at high pressure, e.g. about 27 bar. The gasification system mainly comprises a gasifier and a cyclone with a gravity pipe. The gasifier is a pressure vessel provided with a refractory lining. The lower section of the gasifier is cone-shaped to allow for the increase in the gas volume during the gasification process. The upper section of the gasifier is cylindrical.

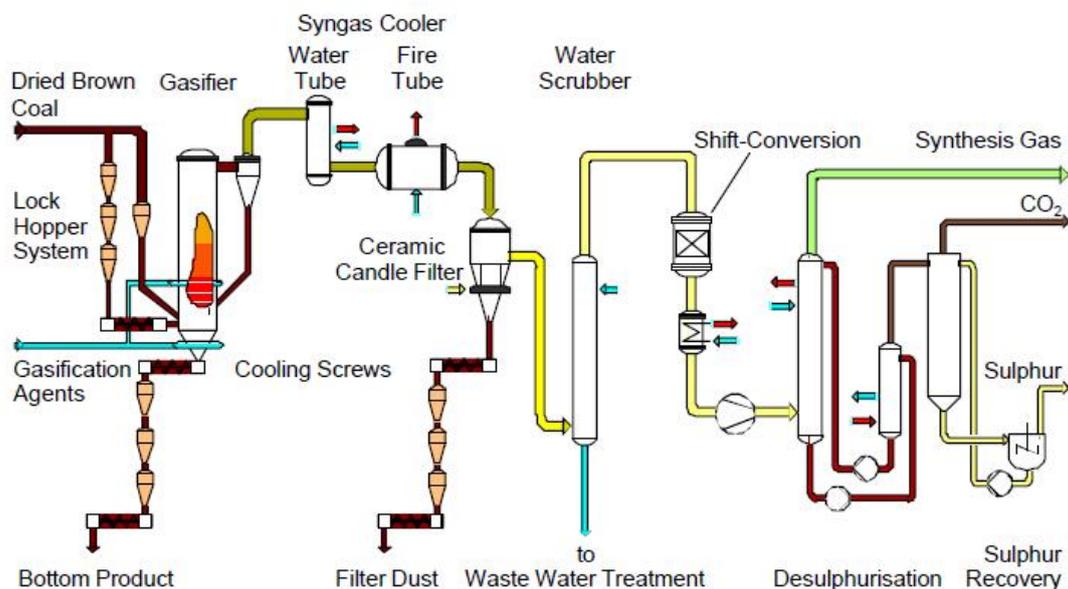


Figure 97. Schematic of the HTW demo process plant at Berrenrath (Ref. Uhde).

The gasifier can be subdivided into two zones:

1. The highly expanded fluidised-bed, which has a relatively uniform temperature (in the order of 700°C when gasifying wood), is the lower zone.
2. The superposed zone is termed "free board" or "post-gasification zone". The gasification agent (air/oxygen) is not only admitted to the fluidised-bed but also into the free board in order to decompose undesirable reaction by-products (tars) and to gasify entrained char by raising the temperature (approx. to 900°C).

The crude gas which leaves the gasifier at the top contains a considerable amount of entrained particulate. The major portion of this particulate is separated from the crude gas in the hot cyclone and returned into the fluidised bed of the gasifier through a gravity pipe.

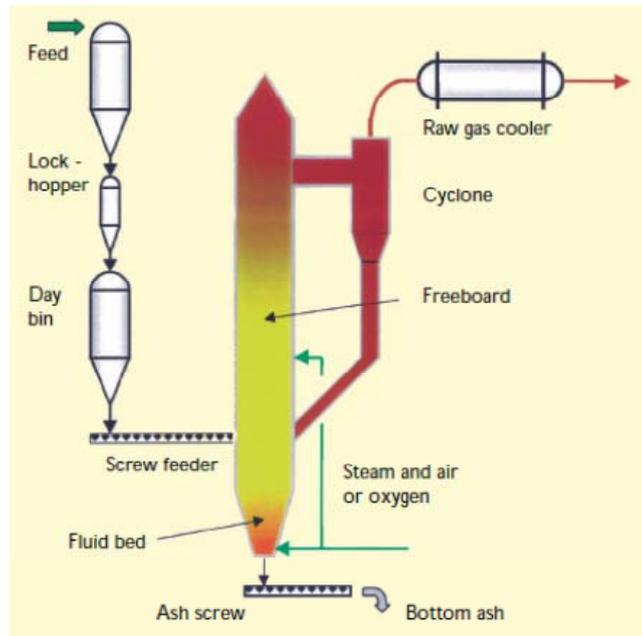


Figure 98. Schematic of the HTW gasification process (Ref. Uhde).

As is the case with the gasifier, the cyclone and the gravity pipe are provided with a refractory lining. The gasification system comprising the gasifier, hot cyclone and gravity pipe is enclosed by a water jacket which is supplied with boiler feed water and operated at atmospheric pressure. The water jacket serves:

- To maintain the entire system at a uniform surface temperature level in order to avoid inadmissible stresses due to differing thermal expansion.
- To protect the pressure shells from superheating in the case of refractory fractures. Such an incident is, however, not very likely to occur.

The wood feedstock is fed into the fluidised bed by means of water-cooled screw conveyors. Gasification residues, termed bottom product, are withdrawn at the bottom of the gasifier. A cooling screw serves for discharging and cooling the bottom product. Due to the small amount obtained, the removal system only consists of one vessel and one cooling screw. The cooling system cool down the crude gas produced in the gasifier from approx. 900°C to approx. 350°C. The heat recovered is used for the generation of high pressure saturated steam. The crude gas cooler is a convective boiler of the fire-tube type arranged horizontally.

The HTW process has predominantly been tested with lignite, municipal solid waste (MSW) and peat in large-scale tests. In addition, these tests were conducted some time ago. The gas composition is listed in below Table.

Tabell 8. Gassammansättning (rågas) för MSW och ved med syre som oxidant (Ref. Uhde)

Table 8. Gas composition (crude gas) MSW and wood with oxygen as oxidant (Ref. Uhde).

Compound	MSW (oxygen)	Wood (oxygen)
Hydrogen	34% vol.	28.6% vol.
Carbon monoxide	35-37% vol.	35.6% vol.
Carbon dioxide	24% vol.	28.8% vol.
Methane	5-6% vol.	6.7% vol.
Higher hydrocarbons		0.3% vol.
Nitrogen		0.1% vol.

F.4 Projects

Since the acquisition of Krupp Uhde into Thyssen Krupp and the reorganization it has been little activity in biomass gasification. The gasification business has been more focused on MSW and coal. However, the HTW process has been further developed and is currently termed HTW Plus.

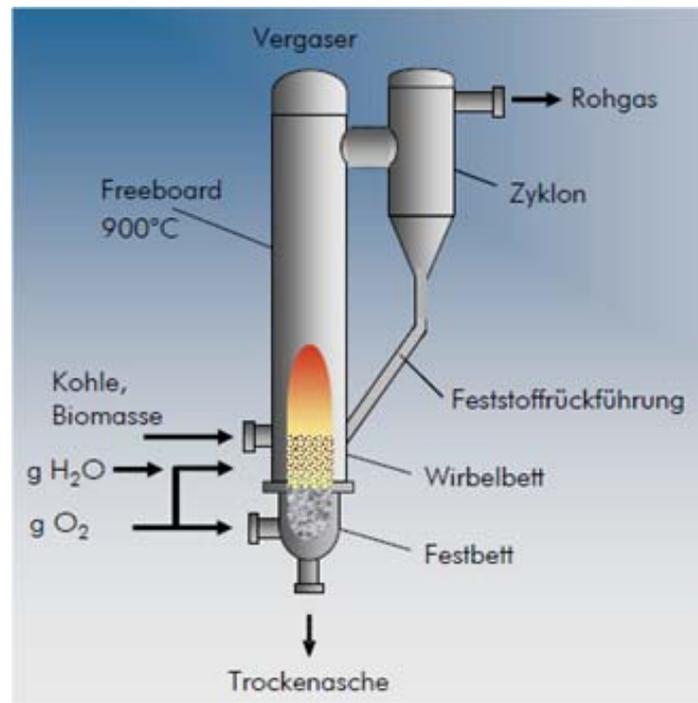


Figure 99. Schematic of the HTW Plus gasification process (Ref. Uhde).

However, Uhde's "Prenflo" PDQ (process with direct quench) gasification technology will be employed in the French-led "BioTfuel" biomass-to-liquids (BTL) Fischer-Tropsch (FT) diesel and jet-fuel project. A torrefaction pre-treatment plant has been installed at 15 MWf capacity to allow the use of a wide range of biomasses. Other project partners include Total, IFP, the French Atomic Energy Board and the industrial oilseed producer, Sofiproteol. The 15 MWf gasifier is scheduled to be built in 2015.

A rather small MSW project has been reported for Sikuku, Japan where Uhde sold a license to Sumitomo Heavy Industries, SHI for a 20 tonnes per day atmospheric plant which was commissioned in 1999 with successful operation first year.



Figure 100. Photograph of the HTW gasifier at Sikuku, Japan (Ref. Uhde).

In addition, Uhde has signed with VärmlandsMetanol an agreement as selected EPC contractor for a 110 MWf methanol plant producing 100 000 tonnes of biomethanol per year in Hagfors with an unclear future startup date. The investment cost is estimated as some 3.5 billion SEK. The current status of the project is very unclear.