VTT RESEARCH NOTES 2511

Advanced Biomass Gasification for High-Efficiency Power

Publishable Final Activity Report of BiGPower Project

VTT TIEDOTTEITA – RESEARCH NOTES 2511

Advanced Biomass Gasification for High-Efficiency Power

Publishable Final Activity Report of BiGPower Project

Edited by
Esa Kurkela & Minna Kurkela

Project Partners
VTT, TUV, Kokemäen Kaasutin, Carbona, RPT, MEL, Norta, GEJ, MTU, BKG, CERTH, TKK, Clear Edge

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Abstract

The BiGPower project was related to the development of 2nd generation high-efficiency biomass-to-electricity technologies, which have the potential to meet the targets of cost effective electricity production from wide range of biomass and waste fuels in size ranges typical to locally available feedstock sources (below 100 MW_e). This project was designed to create the fundamental and technical basis for successful future industrial developments and demonstration projects aiming to commercial breakthrough by 2010–2020. This overall aim was approached by carrying out in pre-competitive manner well-focused R&D activities on the key bottlenecks of advanced biomass gasification power systems.

Three promising European gasification technologies in this target size range were selected to form the basis for the development: 1) air-blow novel fixed-bed gasifier for size range of 0.5–5 MWe, 2) steam gasification in a dual-fluidised-bed gasifier for 5–50 MWe and 3) air-blown pressurised fluidised-bed gasification technology for 5–100 MWe.

In all biomass gasification processes, the product gas contains several types of gas contaminants, which have to be efficiently removed before utilising the gas in advanced power systems. The key technical solutions developed in the BiGPower project were: a) high-temperature catalytic removal of tars and ammonia by new catalytic methods, and b) development of innovative low cost gas filtration.

Three most potential power production cycle alternatives were examined and developed: 1) gas engines, 2) molten carbonate fuel cells (MCFC) and 3) the simplified Integrated Gasification Combined Cycle (IGCC) process. The performance and techno-economic feasibility of these advanced gasification-to-power concepts were examined by carrying out case studies in different European Union.

Preface

The research described herein was carried out during the period 2005–2008 as part of the project “Advanced Biomass Gasification for High-Efficiency Power”. This project, known as the BIGPOWER-project contract no 019761 was coordinated by Esa Kurkela of VTT Technical Research Centre of Finland. BIGPOWER was funded by the European Commission as a STREP project under the 6th Framework Programme. Additional funding was provided by Tekes -the Finnish Funding Agency for Technology and Innovation and by VTT. The work of the project was carried out in co-operation with the following project participants:

R&D organisations supporting industrial development

VTT Technical Research Centre of Finland – VTT	www.vtt.fi
Vienna University of Technology, Austria – TUV	www.vt.tuwien.ac.at
Centre of Research & Technology Hellas, Greece – CERTH	www.certh.gr
Helsinki University of Technology, Finland – TKK	www.tkk.fi

Gasification systems

Andritz/Carbona, Finland	www.andritz.com
Repotec GmbH, Austria – RPT	www.repotec.at
Biomasse Kraftwerk Güssing, Austria – BKG	www.eee-info.net
Condens Oy / Kokemäen Kaasutin Oy, Finland – Condens	www.condens.fi

Power production equipment

GE Jenbacher, Austria – GEJ	www.gejenbacher.com
MTU Onsite Energy GmbH, Germany – MTU	www.mtu-online.com

Catalytic Gas Cleaning and filtration

MEL Chemicals, United Kingdom – MEL	www.zrchem.com

Norta UAB, Lithuania – Norta www.ollo.lt
Clear Edge UK Ltd, United Kingdom – MFILT www.clear-edge.com

Authors of different chapters

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http://www.vtt.fi/proj/bigpower

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1. Introduction

1.1 Project objectives and work packages

The BiGPower project was related to the development of 2nd generation high-efficiency biomass-to-electricity technologies, which have the potential to meet the targets of cost effective electricity production from wide range of biomass and waste fuels in size ranges typical to locally available feedstock sources (below 100 MW_e). This project was designed to create the fundamental and technical basis for successful future industrial developments and demonstration projects aiming to commercial breakthrough by 2010–2020 (Figure 1). This overall aim was approached by carrying out in pre-competitive manner well-focused R&D activities on the key bottlenecks of advanced biomass gasification power systems.

Three promising European gasification technologies in this target size range were selected to form the basis for the development: 1) Air-blow novel fixed-bed gasifier for size range of 0.5–5 MWe, 2) Steam gasification in a dual-fluidised-bed gasifier for 5–50 MWe and 3) Air-blown pressurised fluidised-bed gasification technology for 5–100 MWe.

In all biomass gasification processes, the product gas contains several types of gas contaminants, which have to be efficiently removed before utilising the gas in advanced power systems. The key technical solutions developed in the BiGPower project were: a) High-temperature catalytic removal of tars and ammonia by new catalytic methods, and b) Development of innovative low cost gas filtration.

Three most potential power production cycle alternatives were examined and developed: 1) gas engines, 2) molten carbonate fuel cells (MCFC) and 3) the simplified Integrated Gasification Combined Cycle (IGCC) process. The performance and techno-economic feasibility of these advanced gasification-to-power concepts were examined by carrying out case studies in different European regions.

The workplan of BIGPower was divided into seven R&D workpackages and supporting project management:

WP 1: Advanced gas cleaning
WP 2: Dual Fluid-Bed gasification
WP 3: Novel air-blown gasification
WP 4: Improved pressurised gasification
WP 5: Advanced gasifier engine plants
WP 6: Biomass Gasification Molten Carbonate Fuel Cell system development
WP 7: Case studies and techno-economic assessment.

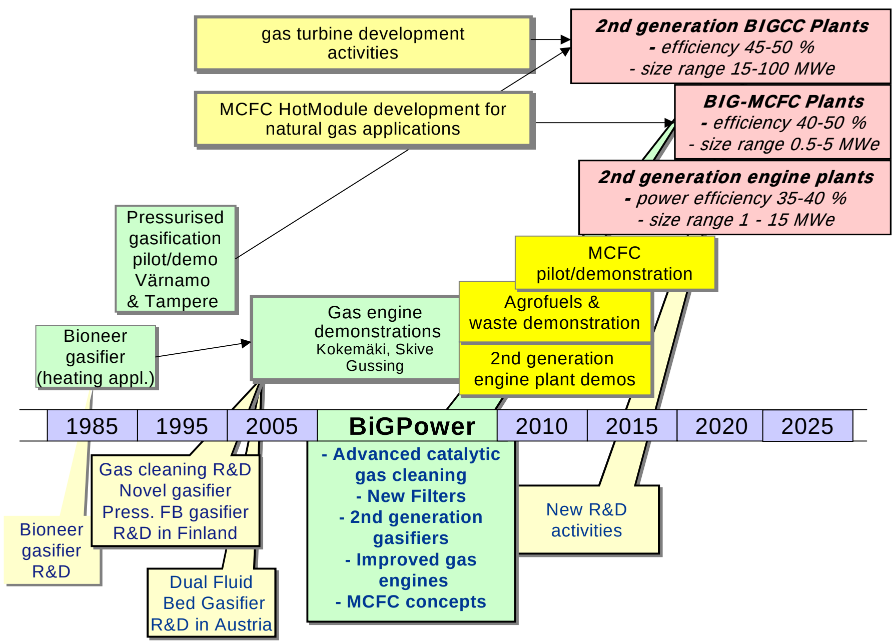

Figure 1. Road map for the development, demonstration and commercialisation of the BiGPower technologies.

All the technologies selected to this project have the required potential to meet the targets of efficient, reliable and economically attractive power production. In addition, these technologies cover the whole range of most potential biomass-to-electricity production capacities from 0.5 MWe up to 100 MWe. Only the very small scale (kW-scale) and on the other hand the 500-1000 MWe concepts were excluded from this project.

The key objectives of the project are presented in Table 1.

Table 1. The specific objectives of the project.

No.	Objective	WP
1	**To develop and test in laboratory and bench-scale new catalytic tar decomposition methods, which can fulfil the following targets:** - over 99% removal of tars and/or final tar concentration is below 50 mg/m^3n - potential for investment cost reduction of at least 30% compared to the present-state-of-the-art nickel monolith catalyst systems - operation at < 800 °C temperature without soot formation or ash-deposition problems typical to present high-temperature nickel-based systems operating at ca. 900 °C - not sensitive to poisoning by alkali-metals, chlorine or sulphur.	WP1
2	**To develop and test advanced filter media,** which is at least 30% less expensive than the present rigid ceramic candle filters or sintered metal filters and which can be operated with biomass-derived gases at 550–850 °C temperature window without tar/soot blinding problems	WP1 WP4
3	**To develop methods for improving the performance of Dual-Fluid-Bed steam gasification process by increased fuel flexibility, lower costs and improved reliability:** - to develop and test in 100 kW PDU plant new ideas for innovative fuel feeding systems to avoid steam leakage in over-pressure operation – with 50% lower electricity consumption compared to commercial feeding systems, and which produce only low pressure fluctuations in product gas - to study and test in the 100 kW PDU plant methods for avoiding ash-related problems with 4–5 most potential biomass fuels e.g. forest residues, willow, sewage sludge, saw dust, etc. - to study in-situ tar decomposition with active bed materials by PDU-scale tests aiming to improved performance of the final gas cleaning train – the targets in detail are: reduced investment cost by 5%, lower maintenance costs by 10% - to design and test in slip stream of Guessing plant an optimised catalytic gas cleaning system based on the new developments of the project – target of at least 3 000 hours of long-term operation - to test 1–3 of the most successful new developments of the project in the Guessing demonstration plant.	WP2
4	- **To develop methods for improving the performance of Novel-fixed bed gasification process by increased fuel flexibility, lower costs and improved reliability:** - to develop and test in bench-scale new ideas of in-situ catalytic tar decomposition in the upper part of the gasifier - to design and test an optimised catalytic gas cleaning train for Novel gasifier with equal performance but at least 30% lower costs than present gas cleaning system - to study the zero-emission gasifier concept including scrubber effluent recycling.	WP3

5	- **To study and test new ideas for 2nd generation pressurised fluidised-bed gasification process in IGCC and in innovative large-scale gas engine applications** - to develop and evaluate improved process concepts which have potential to realise IGCC concepts economically already at 15–30 MWe instead of the present minimum size of 50 MWe - to develop and evaluate innovative gas engine concepts based on intermediate pressure gasification - to study and test in a 300 kW PDU-rig novel hot gas cleaning methods which have the potential to avoid the use of expensive and problematic raw gas coolers and catalytic deNOx systems in the BIGCC plants.	WP4
6	**To develop and evaluate 2nd generation gas engine systems optimised for biomass gasification gas** - to improve engine performance and to reduce specific investment cost by 15% - to design gasifier-engine concepts for 1–10 MWe with biomass-to-electricity efficiency 35–40% and investment cost of 2 000–2 500 €/kWe - to develop near-zero emission gasifier-engine power plant process concepts with respect to CO, hydrocarbon and NO_x emissions.	WP5
7	**To create design basis for high efficiency power and heat production systems based on advanced biomass gasification and optimised MCFC system aiming to** - to create an optimised MCFC design basis and performance analysis both for air-blown and steam gasification gas - to achieve technical readiness for pilot testing in ca. 250 kW HotModule scale - to design gasifier-MCFC concept for 0.5–5 MWe with 40–50% eff. and 2 500–3 000 €/kWe.	WP6
8	**To define and evaluate optimised biomass-gasification-to-power systems in different surrounding conditions of Europe** - to carry out techno-economic case studies in Finland, Greece and Austria in order to find most promising applications for advanced biomass gasification and to create basis for industrial follow-up projects.	WP7

1.2 Participants

The BiGPower consortium was composed on well-balanced group of research organisations and innovation-oriented industrial companies:

- two large national research centres (VTT from Finland and CERTH from Greece)
- two top-quality technical universities (TUV from Austria and TKK from Finland)
- three SME companies as suppliers of innovative gasification technologies (Kokemäen Kaasutin and Carbona from Finland and Repotec from Austria)
- one SME company specialised in plasma coating technology (Norta from Lithuania)
- one filter developer and supplier (Clear Edge from UK)

- one developer and supplier of catalyst powders (MEL Chemicals from UK)
- one leading fuel cell developer and supplier (MTU from Germany)
- one leading supplier of advanced gas engines (GE Jenbacher from Austria)
- two owners of the gasification demonstration plants (BKG from Austria as a partner and Kokemäen Lampö Oy as subcontractor to VTT).

The BiGPower project was realised by 13 participants (Table 2). VTT acted as the coordinator for this project.

Table 2. List of participants.

Participant name	Participant short name	Country
Technical Research Centre of Finland	VTT	Finland
Vienna University of Technology	TUV	Austria
Kokemäen Kaasutin	Kokemäen Kaasutin	Finland
Carbona Oy	Carbona	Finland
Repotec GmbH	RPT	Austria
MEL Chemicals	MEL	United Kingdom
Norta UAB	Norta	Lithuania
GE Jenbacher	GEJ	Austria
MTU Onsite Energy GmbH	MTU	Germany
Biomasse Kraftwerk Guessing	BKG	Austria
Centre of Research & Technology Hellas	CERTH	Greece
Helsinki University of Technology	TKK	Finland
Clear Edge UK Ltd	Clear Edge	United Kingdom

2. Work performed and achieved results

A summary of each work packages with respect to achievements towards objectives over the whole project duration is presented in the following.

2.1 WP1 Advanced Gas Cleaning

The overall aim of WP1 was to develop second generation catalytic gas cleaning methods, which would be technically more efficient and/or less expensive than the nickel-monolith-based systems that are entering to the commercial market today. This WP also provided new information and advanced methods, which helped in performing the other WP's of the project. In addition to new developments, WP1 also contributed significantly to the general gas cleaning science in the forms of several papers and poster presentations.

The overall aim of WP1 was broken to the following specific objectives:

1) To develop and test in laboratory and bench-scale new catalytic tar decomposition methods, which can fulfil the following targets:

- over 99% removal of tars and/or final tar concentration is below 50 mg/m^3n
- potential for investment cost reduction of at least 30% compared to the present-state-of-the-art nickel monolith catalyst systems
- operation at < 800 ^{o}C temperature without soot formation or ash-deposition problems typical to present high-temperature nickel-based systems operating at ca. 900 ^{o}C
- not sensitive to poisoning by alkali-metals, chlorine or sulphur.

2) To develop and test advanced filter media, which is at least 30% less expensive than the present rigid ceramic candle filters or sintered metal filters and

which can be operated with biomass-derived gases at 550–850 ^{o}C temperature window without tar/soot blinding problems.

3) To study and test gas cleaning from chlorine and sulphur to sub-ppm levels required in fuel cells.

WP1 was further divided in five subtasks according to the work content. The following sections give an overall description of the tasks.

Task 1.1 Development of new oxide catalyst powders

The basic idea of this task was to develop new oxide based catalyst powders, which can be used in developing and producing new advanced catalysts for gas cleaning processes studied in this project. Catalyst preparation technologies studied were

- plasma spraying method
- washcoating method.

Previous work carried out by VTT indicated that zirconia powders were useful for this application, but the composition and manufacturing route had not been fully optimised. In order to find the optimum product, a sample matrix was prepared consisting of 24 different powders. These were prepared from zirconium hydroxide with 4 different compositions. Furthermore, three different process routes were employed: G2, G3 and G4, which are known to give different properties for the powders. Most of these hydroxide precursors were readily available, but others required development specifically for this project

Task 1.2 Development of cost effective catalyst elements

Plasma spraying technology gives a possibility to prepare cost effectively metal substrate catalysts that have high adhesion of the catalyst layer to metal foil combined with high catalytic activity. Attrition resistance of plasma coated catalyst is excellent compared to traditionally prepared washcoated catalysts. Consequently, plasma coated metal catalysts are a very interesting option considering the demanding conditions in gasification and reforming processes. Two different catalyst types were studied and developed in this project: 1) zirconia and 2) nickel/alumina coated.

Plasma coated catalyst samples were tested for tar and ammonia decomposing activity by making laboratory tests with simulated gasification gas. The best catalyst formulation was prepared in larger scale (Figure 2) and tested by placing it in a full size reformer unit for extended time test.

Figure 2. Larger scale plasma coated catalyst samples.

Task 1.3 Advanced monolith catalysts

The first objectives of this task were to prepare washcoated ceramic monolith catalysts from powders produced by MEL Chemicals. These catalysts were then tested by laboratory scale unit or in slip stream and full size reformers in WP3. As an addition to the original plan also catalyst deactivation studies with Zr and Ni catalysts was carried out as agreed in the mid-term meeting of the project.

The catalyst powders were coated on the monoliths which were tested with atmospheric fixed bed reactor with the synthetic gas mixture containing CO, CO_2, CH_4, C_2H_4, H_2, N_2, H_2O, H_2S, NH_3 and tar. A mixture of naphthalene and toluene was used as a tar model compound. Oxygen was added to enable the oxidation reactions. Conversions of naphthalene and tar model compound were calculated from the reactor mass balances.

In general the samples had differences in the quality of wash coatings between the different dopants and the catalysts preparation methods had to be adjusted in case of each dopant for successful wash coating on monoliths. The biggest influence on the wash coating properties was detected to be the dopant of the zirconia.

Task 1.4 Innovative catalyst filters

The main objectives of the work on catalytic filters can be summarized as follows:

- To develop a ‘low cost’ innovative ceramic filter that will provide simultaneous abatement of particulates and gas phase tars, to be placed between the gasifier and heat engine in the process flow.
- These filters should have no soot and tar blinding tendencies.
- The filters should operate in the temperature range 600–800 °C.
- The filters should exhibit up to 80% tar decomposition activity in the temperature range 700–850 °C.

The generic technology around which this development proceeded was the Cerafil™ range of hot gas filters produced by Madison Filter. These filters have been employed in hot gas particulate removal filtration applications for over ten years, with several hundred reference-sites available. The filters consist of a single piece rigid filter element. The elements are comprised of a low-density fibrous structure, which is entirely self-supporting. They are commonly employed in applications where standard bag-house filter media cannot be used due to high operating temperatures. The generic technology of utilizing the Cerafil™ hot gas dust filtration structure, impregnated with a catalyst, formed the basis of the development work in WP1.4.

The testing of the prepared filter samples was performed by making laboratory tests for small filter pads. In addition full-scale elements were also produced in order to demonstrate the scalability of the production method.

Task 1.5 Sulphur and chlorine removal

This task was realised as a literature survey by TUV the objective being removal of sulphur and chlorine to sub-ppm levels required in fuel cell applications of WP6. According to literature many different parameters influence desulfurization. Wet processes needs large amounts of water and furthermore chemical processes are usually not used for separation processes, because desorption is difficult due to the chemical bonding. Thus, it turned out that recently only metal oxide mixtures of reactive and inactive metal oxides with more or less high capacity have been combined and tested in various studies.

2.2 WP2 Dual Fluid-Bed gasification

The objectives of WP2 were to develop methods for improving the performance of Dual-Fluid-Bed steam gasification process by increased fuel flexibility, lower costs and improved reliability. This overall aim was broken into the following specific objectives:

– to develop and test in 100 kW PDU plant new ideas for innovative fuel feeding systems to avoid steam leakage in over-pressure operation – with 50% lower electricity consumption compared to commercial feeding systems, and which produce only low pressure fluctuations in product gas
– to study and test in the 100 kW PDU plant methods for avoiding ash-related problems with 4–5 most potential biomass fuels
– to study in-situ tar decomposition with active bed materials by PDU-scale tests aiming to improved performance of the final gas cleaning train – the targets in detail are: reduced investment cost by 5%, lower maintenance costs by 10%
– to design and test in slip stream of Güssing plant an optimised catalytic gas cleaning system based on the new developments of the project – target of at least 3 000 hours of long-term operation
– to test 1–3 of the most successful new developments of the project in the Güssing demonstration plant.

These WP2 objectives were approached by carrying out R&D activities in the following three Tasks. These Tasks were carried out in close co-operation with the Austrian partners TUV, Repotec and BKG. Good results were achieved at TUV test gasifiers for a wide range of alternative biomass fuels and new results on the effects of different potential bed materials on tar formation and ash sintering were created. On the practical development side, new methods for feeding of biomass into the gasifier were developed and different ways of fuel drying and gas cooling was also thoroughly studied. Some of the new findings and developments (such as new feeder, different bed materials and fuel mixtures) were also tested in the full-scale demo plant in Güssing. Thus, the project provided a lot of relevant input for planning next generation dual-fluid-bed gasification plants.

The slip stream catalyst testing (Figure 3) at Güssing plant turned out to be technically challenging and the targeted operating hours could not be met. In addition, the catalyst reactor could not be operated at an optimal temperature. Thus, the results on this point were not fully satisfactory. For the possible future experiments the design of the reformer must be changed and a new reformer and new heaters are necessary. However, despite these problems tars could be reduced by more than 80% during several short test runs of several hours up to three days. The control system as well as the cleaning and regeneration of the catalysts has been implemented successfully.

Increased fuel flexibility of dual fluid-bed process

The fuel feeding system, consisting of a plug screw followed by a scarify screw, was firstly tested on laboratory scale at TUV with different wood chips (size fraction, water content were varied) and various designs of the plugging part of the screw were tested.

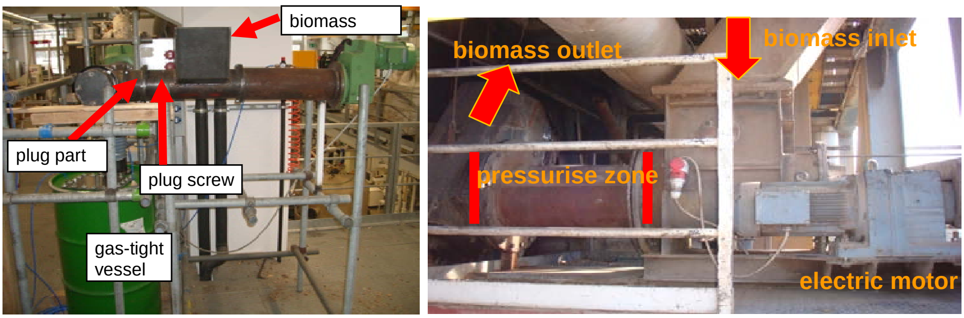

Figure 3. Fuel feeding test equipment at TUV (left picture) and the full-scale feeders constructed at Güssing (right picture).

With the results of these tests the feeding system of the large scale plant in Güssing was adapted. BKG, Repotec and TUV worked together and installed the most successful option based on the results from the small scale tests. It was observed that the screw worked very well and only some problems with deposits inside the connection ways existed. Although several detail improvements have been made it remained to be a critical and service intense part of the technology. Furthermore it turned out, that one single system cannot handle the different behaviour of all possible fuels. Therefore a separate feeding system for non plugging fuels like e.g. pellets has been engineered.

Tests with systematic variation of the fuel quality were performed at the 100 kW gasifier at TUV. Particle size, water content and ash content were varied. Straw coke from a pyrolysis process has been mixed with different additives to determine the influence of these additives on the ash melting behaviour. It was shown that addition of about 5 wt% of kaolin resp. limestone increased the beginning of melting temperature by about 200 °C. However, experiments with straw pellets as fuel and calcite as additive to the bed material (olivine) lead to blockings of the siphon due to agglomeration of olivine and calcite. Promising results were achieved with straw/wood mixed pellets. The results set a good data base on the behaviour of a broad range of possible fuels.

Improved tar decomposition in the gasifier by catalytic bed materials

Wood/straw pellets with mixtures of 80/20 resp. 60/40 (weight) were tested at a gasification temperature of about 800 °C using Olivine as bed material. No agglomeration occurred within these tests. Previous experiments with Calcite as additive to Olivine lead to blockings due to agglomeration of these materials, independent on the fuel.

Moreover, tests with pure Calcite as bed material and straw pellets, wood pellets and wood chips as fuel were accomplished. The attrition was in the same range as for experiments with Olivine and the gas composition showed similar values. Tar values measured for Calcite were in the order of one magnitude lower than for Olivine.

At the 8 MW gasifier BKG and TUV run a test with calcite as bed material. After around 12 hours the test had to be stopped. Problems were attrition of bed material and too small particles to be separated by the bag filter. However, the measurements showed that the tar amount was lower than with Olivine as bed material due to the catalytic activity of CaO.

Advanced gas cleaning development and testing

Several tests with the slip stream reactor (Figure 4) for catalytic tar reforming were carried out at Guessing. An operation temperature of about 900 to 910 °C was intended. Since the inner part of the reformer is not gas- and dust-tight, ungasified carbon was transported to the heaters and thus the spiral-wound filaments of the heaters were destroyed. Finally, the reformer was in operation for about two days at temperatures of slightly above 800 °C. Despite the low temperature a reduction of the tars by 80% could be achieved. In general, the tests showed no deactivation of the catalyst and the reformer could finally be operated as planned.

For the long term experiments of more than 3 000 hours, the design of the reformer has to be changed and a new reformer and new heaters are necessary. These measures could not be fulfilled within the BiGPower project.

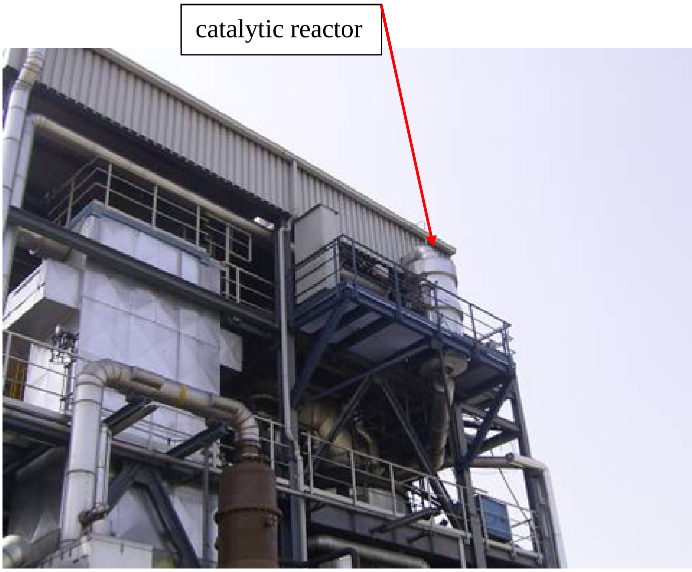

Figure 4. Slip stream catalyst testing facility at Güssing.

2.3 WP3 Novel fixed-bed gasifier

The main objectives of the work in this WP were to develop methods for improving the performance of Novel-fixed bed gasification process by improved tar control, lower costs and improved reliability. In short

- to develop and test new ideas of in-situ catalytic tar decomposition in the upper part of the gasifier
- to design and test an optimised catalytic gas cleaning train for Novel gasifier with equal performance but at least 30% lower costs than present gas cleaning system (long extended time test in a slip stream test reactor)
- to develop zero-waste-water gas cleaning concept based on recycling scrubber effluent.

WP3 was performed as joint effort between Condens/Kokemäen Kaasutin and VTT. VTT was responsible for the measurements, data acquisition and reporting, Condens/Kokemäen Kaasutin on the plant operations, process design, maintenance and assembly work. WP3 was divided in subtasks according to the work content as follows:

Task 1.1 In situ tar decomposition

The main idea of this task was to find a low-cost and robust catalyst system, which could be integrated into the upper part of the Novel gasifier. Successful realisation of this subtask would have made it possible to utilise conventional low-temperature filtration (150–250 ^{o}C) without secondary catalyst reactor and would have significantly reduced the cost of secondary catalyst unit in applications aiming to complete tar removal. The task was realised by making laboratory test and also by performing plant tests with special test catalysts. This task turned out to be rather challenging and in the tests carried out at the Kokemäki demonstration plant, the catalyst samples lost their activity due to too severe operating conditions during start up, shut downs procedures as well as in some interruptions in plant operation. Better control and automations would be needed to keep the operating conditions in the gasifier always in allowable limits set by in-situ catalyst.

Task 1.2 Zero-emission Novel gasification process development

The emission reduction methods of the Novel CHP process were studied in two supporting subtasks. The principal targets were that 1) the catalytic reformer would decompose most of the tars so that the final gas cooling and cleaning could be carried out using conventional bag house filters and 2) the water scrubbing system could be operated without the formation of poisonous tar-containing waste water streams.

Reformer development

The main objective in the task was to develop and test an improved tar and ammonia reformer. In the first phase, new second generation reformer design was tested using slip-stream from the Kokemäki plant (Figures 5 and 6). It utilized the advanced catalysts prepared in WP1. Several tests were carried out with the slips stream reformer and the last test run with optimised catalyst formulation lasted for 750 hours and the catalyst activity remained very high throughout this test.

The second testing phase involved testing of the new catalysts and reformer design n the full gasifier stream of the Kokemäki demonstration plant. The work was performed by VTT and Condens/Kokemäen Kaasutin with assistance from the Kokemäen Lämpö Oy (subcontractor).

The catalysts used in this task were ceramic monolith catalysts. The monoliths are cordierite substrate, which were washcoated with a special method developed at VTT. This method has proven to be suitable for various laboratory, bench and full scale monolith samples. The method has been modified to be suitable for various commercial monoliths available from different manufacturers. Industrial size monoliths based on MEL's Zr-powders were mounted in the full-scale reformer of the Kokemäki plant (Figure 5). The reformer design was also improved at the same time.

The reformer was operated at temperature range 700–900 °C at 1–4 MW capacity range of the plant. Catalyst loading of the reformer included zirconia and nickel monoliths, further details of the catalyst layout and reformer are proprietary information. The operation conditions of the reformer were optimised to keep the temperature high enough so that sufficient tar conversion could be achieved. Higher conversions can be easily achieved using higher operation temperatures, but this would mean decrease in gas heating value, which in turn seemed to be critical for the engine. With this operation mode at optimised conditions heavy tar conversion of 75% and naphthalene conversion of 50% was achieved.

In conclusion, the preliminary results indicated that the reformer with new zirconia monoliths operated as expected and the heavy tar conversion could be kept at acceptably high level. Accordingly, the engine could be operated several weeks at partial load without tar clogging problems.

2. Work performed and achieved results

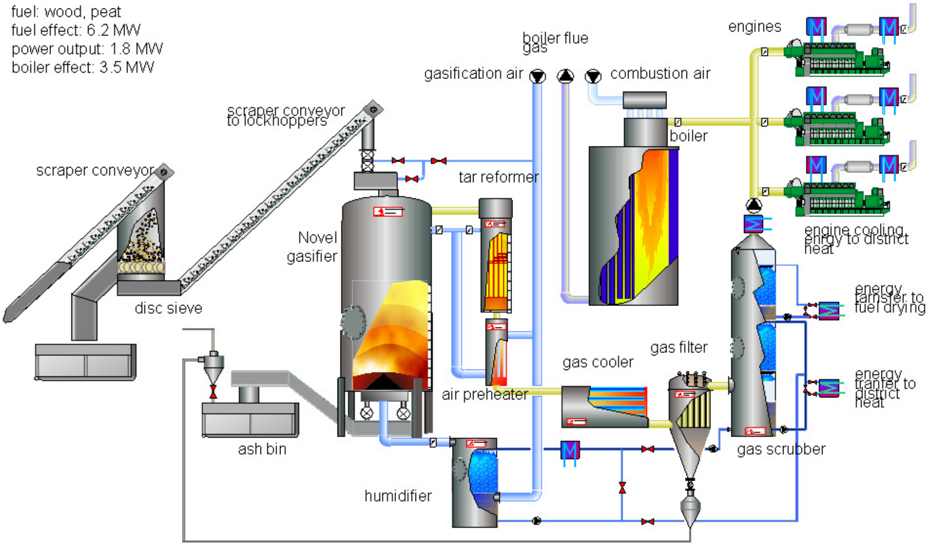

Figure 5. The Kokemäki Novel CHP plant as planned to be realised (during the project only one gas engine existed and the rest of gas is combusted in a district heating boiler).

Figure 6. The slip stream catalyst testing facility connected to the raw gas line between the Novel gasifier and the main stream reformer.

Effluent water

All the wastewater generated in the Novel gasification process at Kokemäki power plant originates from the product gas scrubber. The amounts of effluents that are developed in the process are moderate because practically all the waste water is recycled back into the process. The only effluent that results from the Novel process is a stream of condensed water that is fed in the process in the form of feedstock moisture and has to be removed in order to avoid excess water accumulation in the process. For a gasifier that is operated with a capacity of 4 MW_{fuel} and with average feedstock moisture of 25% this results in a waste water stream of about 4 l/min. At Kokemäki Novel plant the product gas is scrubbed in two phases and all the water soluble impurities are passed on to water. At the bottom of the scrubber there is sedimentation tank, where impurities are separated from the water. From the bottom of the scrubber, the sedimentated grime is pumped to the gasifier feeding tank from where it is fed back to the process. The scrubber water is also used in the gasification air humidifiers where evaporative part of the contaminants is stripped off and thus recycled back into the process.

The Kokemäki plant seemed to meet the environmental wastewater directives. This was achieved mainly due to the catalytic gas cleanup that eliminated the need of water or solvent scrubbing of the contaminants. Hence, wastewater was formed mainly from fuel moisture by condensation in water scrubber/cooler. Due to the internal water recycling and stripping processes the volatile organic contaminants were recycled into the gasifier and resulting wastewater contained very low concentrations of organics. The clean biomass fuels and efficient gas filtration ensured that the contents of heavy metals in the wastewater were very low.

2.4 WP4 Improved pressurised gasification process

WP4 was related to the further development of Integrated Gasification Combined Cycle processes based on pressurised fluidised-bed gasification. Carbona ja CERTH carried out detailed process modelling and evaluation work, while VTT, TKK and Madison Filter carried experimental R&D on hot gas cleaning.

The process studies showed that high efficiency power plants concepts with biomass-to-electricity efficiency of 45% can be designed at larger scale of 50–60 MWe and relatively high efficiency of the order of 40% can also be achieved at 15 MWe scale. Promising possibilities for demonstrating this technology were also suggested in applications where this technology is integrated to existing coal or natural gas fired power plants.

In the experimental part of WP4, the most important result was the replacements of SiC-ceramic candle filters by less expensive and thermally more robust fibre filters of Madison Filter. Successful tests where the filter unit was operated at below 580 ^{o}C, were carried out with an overall operating hours off ca. 600. Trials to increase the filtration temperature to above 600 ^{o}C failed due to formations of a sticky dust cake.

In the area of ammonia and tar decomposition, two alternatives were tested on laboratory scale by TKK and finally the use of two-stage reformer based on Zr- and nickel-catalysts was tested at VTT's PDU plant. The extended-time test of nine days was successfully carried out in the final year of the project. The main results of WP4 are presented in the following.

Process studies

Within the WP4 CERTH/ISFTA made detailed process models of power cycles based on the pressurized air-blown gasification and different gas turbine cycles. The process model formulation and mass and energy balance computations were performed with Aspen Plus software package. Power island components were simulated with the aid of the Gatecycle software which can handle more easy closed steam cycle calculations. The established models were then used in WP7 in order to appraise the performance and costs of these concepts in selected case studies in Greek power production conditions.

In the beginning of the project, Carbona evaluated the potential of existing gas turbines for the biomass-IGCC power plant applications. The survey of potential gas turbines revealed that in short term there are only few alternatives of European origin with a reasonable efficiency available for the purpose, i.e. GT10 (11,5 MWe) and Frame-6B (43 MWe) of General Electric design. After preliminary studies and careful considerations Carbona selected for detailed evaluation the following basic process alternatives:

- 16 MWe IGCC plant concept
- 65 MWe IGCC plant concept
- IGCC integrated to an existing big fossil power plant (compound cycle arrangement).

All the alternatives have an integrated belt dryer in the plant process, i.e. the district heat level energy needed for drying is taken from the plant process. In order to facilitate the plant operation without interruptions in fuel supply, biomass receiving, handling and storing systems have been included in plant concepts, too. The new power concepts have been kept as simple as possible, because this was found feasible in respect of total efficiency, necessary investments and life cycle costs together with anticipated operational availability.

The final results of the Carbona studies are summarised in Table 3. The net efficiencies are presented with and without the fuel dryer. In usual case, the biomass fuel is wet and when drying is carried out using low-temperature waste heat, the overall efficiency from the LHV of wet biomass to electricity is improved when compared to the use of dry feedstocks. For comparison, this table includes also data on a concept alternative based on aeroderivative LM2500 gas turbine as calculated by CERTH. That calculation was based on their local woody biomass and their computer codes.

Table 3. Summary of the H&M balances for different stand-alone biomass IGCC concepts evaluated under BiGPower.

		GE10	**GE Frame-6B**	**GE LM2500**
Biomass input (AR), moisture content 50%	kg/s	4.30	16.02	
Water evaporation from fuel in dryer	kg/s	1.59	6.01	
Drying heat demand	MJ/s	5.80	21.63	
Biomass input (AF), moisture content 20%	kg/s	2.68	10.01	4.86*
Gasification air input	kg/s	4.02	15.01	7.30*
Gasification steam input	kg/s	0.24	0.92	0.46*
Gasification pressure	bara	23.9	20.6	27.1*
Product gas flow to GT	kg/s	7.11	26.52	13.35
Product gas LHV	kJ/kg	4464.6	4464.6	4494
Biomass input (AF, LHV)	MWth	40.23	150.1	82.6
Gas turbine power output	MW	11.55	44.01	25.10
ST power output, if drying heat extracted	MW	5.26	24.20	-
ST power output, no drying heat extraction	MW	6.09	27.37	9.60
Auxiliary power need with/without dryer	MW	1.56/1.33	5.08/4.48	-/2.70*
Total power output with/without dryer	MW	15.25/16.31	63.13/66.90	-/32.00
Net efficiency with/without dryer	%	37.9/40.5	42.1/44.6	-/38.7

* anticipated by Carbona

In addition to stand alone biomass-IGCC concepts, Carbona and CERTH also evaluated alternatives where pressurised gasification and gas turbine cycle were integrated to large-scale coal-fired power plants with existing steam cycles. The replacement of fossil fuels by biomass in normal coal fired power boilers has been noticed in practice to be possible only up to 5% of the fuel input. By gasifying biomass at first its share in firing can be increased essentially without affecting the steam cycle performance.

An advanced option for biomass utilization in an old big steam power plant is to modify it to a compound cycle. There a gas turbine with a heat recovery boiler is integrated to the steam turbine cycle for feed water preheating and eventually also for generating superheated admission steam for the turbine. This kind of solution allows even up-rating of an existing big fossil condensing power unit by using biomass. An optimal combination in that respect would be a fossil fuel fired power plant with 160–180 MWe reheat steam turbine compound with a pressurized biomass IGCC consisting of GE Frame-6B gas turbine and the heat recovery boiler system.

As a reference case Carbona studied one Finnish fossil 170 MWe condensing power plant, which has quite high power generation efficiency already due to excellent cooling water conditions. The detailed results are presented in deliverable D44 and in case study reports. Table 4 summarises the results of Carbona on this promising alternative for incorporating biomass utilisations to existing large-scale coal-fired power plants.

Table 4. Summary of the compound cycle performance calculation results (170 MWe reheat ST, Frame-6B GT & pressurized biomass gasification) (by Carbona).

		Basic ST cycle Finnish 170 MWe power plant	**Compound cycle** (GE Frame-6B)
Fossil fuel input	MWth	379.7	370.2
Biomass input	MWth	0	150.1
ST power output	MWe	169.7	191.7
GT power output	MWe	0	44.01
Air booster compressor	MWe	0	1.85
Total power output	MWe	169.7	233.9
Process efficiency	%	44.7	44.9
Renewable factor (heat input)	%	0	28.8
Renewable factor (power output)	%	0	27.4

Experimental R&D on gas cleaning

The simplified IGCC process based on pressurised air-blow gasification and hot gas filtration was developed in Finland in early 1990's. The basic gasification and gas filtrations concept was firstly tested at VTT's PDU test rig and then successfully demonstrated at two pilot plants in ca. 20 MW_{fuel} size range (Tampere and Värnämo). At these plants, the product gas was cooled from gasification temperature to 350–550 °C and then filtered by ceramic candle filters or metal filters. The experiences with ceramic candle filters were not always straight forward. In some occasions filter elements were broken and there were also problems with increasing pressure drop and leaking seals between the filter elements and the tube sheet. At Värnämo the ceramic candle filters were replaced with even more expensive metal candle elements.

The aim of BiGPower work in WP4 was to replace the expensive and rather sensitive rigid ceramic candle elements by less expensive and more robust ceramic fibre elements of Madison Filter. In addition, the original aim was to increase the filtration temperature to above 600 °C, which would have decreased the need for gas cooling in the overall IGCC process.

The filtration experiments were carried out at the PDU-scale pressurised fluidised-bed gasification facility of VTT illustrated in Figure 7.

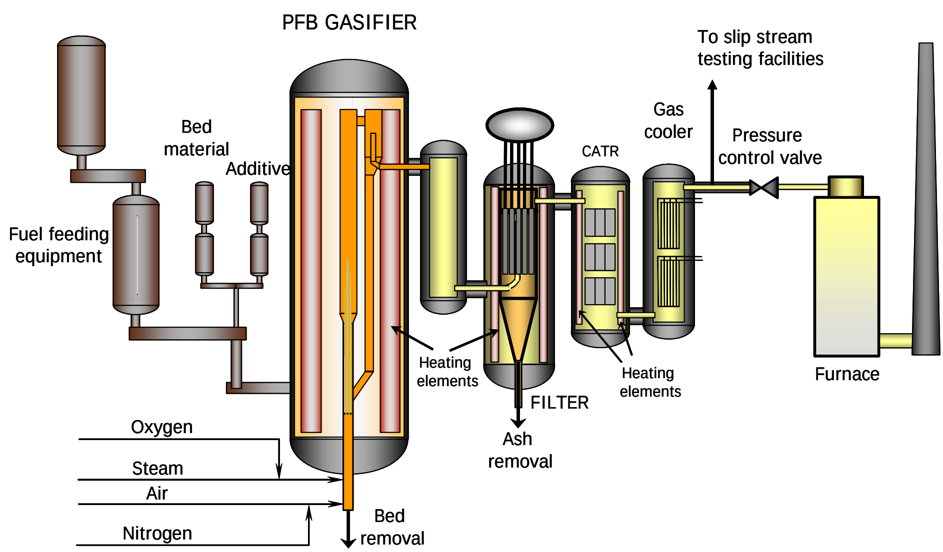

Figure 7. Schematic diagram of the Pressurised fluidized bed gasification PDU (500 kW, VTT Espoo, Otaniemi).

Previously used SiC filter candles were replaced by a set of 12 fibre filters supplied by Madison Filter. Initial test runs with both filter types were devoted for testing the possibilities for increasing the filtration temperature. However, it turned out that the pressure drop of the filter unit was inevitably increasing always when the operation temperature was increased to above 600 ^{o}C. As this phenomenon could not be avoided by simple changes in gasifier operating conditions, it was decided to continue these studies on a laboratory scale test arrangement, while the PDU-scale tests were continued using filters at 500–550 ^{o}C.

The results and experiences obtained with the fibre filters of Madison Filter were as follows:

- Stable pressure drop of 10–25 mbar was achieved at all tests where the filters were operated at below 580 ^{o}C. Pulse cleaning was effective and the dust could be removed without problems. No filter failures took place during the tests. Total number of operating hours under biomass gasification conditions was ca. 600 and almost 1 000 hours when also the start-up and cooling periods are taken into account.
- The isokinetic particulate samples were clean indicating total filtration.
- The alkali metal concentrations were determined at two test runs operated with different wood fuels. In both cases the total concentration of sodium and potassium was below 0.05 pp-wt.
- The filter elements could also stand well shut down and start-up procedures as well as oxidation of the dust cake (after unsuccessful trials at above 600 ^{o}C filtration temperature).

Biomass gasification gas contains impurities such as tar, sulphur and ammonia. Typically, the amount of ammonia in the product gas is 1 000–10 000 ppm. The removal of ammonia is essential in order to prevent NO_x emissions in downstream burners, gas engines, or gas turbines. The ammonia can be removed by scrubbers, but cleaning of the produced waste water is complex and expensive. Selective catalytic oxidation (SCO) of ammonia at high temperatures offers an efficient alternative for ammonia removal. This would make it possible to avoid expensive deNOx systems after the gas turbine. A series of laboratory tests were carried out by TKK at atmospheric and high pressure test reactors located at VTT. The conclusions of the studies were as follows:

- At atmospheric pressure, high conversion of ammonia could be achieved by best copper-based catalysts at temperature window of 400–600 ^{o}C, which is also suitable operation temperature of filtration. Thus, this method for controlling nitrogen compounds could be rather promising for low-pressure applications of biomass gasification.

- Unfortunately the ammonia conversion with copper catalysts was low (generally below 30%) at elevated pressures and thus it was concluded that this method is not promising enough to be continued on PDU-scale experiments.
- Additional tests with nickel-based catalysts gave good results and confirmed previous VTT findings that ammonia decomposition can be effectively catalysed by nickel-based catalysts.

PDU-scale gasification and gas cleaning tests with extended operation time were carried out in the final year of BiGPower project by VTT. The studied process concept was based on the following steps:

- air-blown gasification at 850–900 ^oC using a mixture of limestone/dolomite and sand as the bed material
- gas cooling to below 600 ^oC in simple gas cooler after the recycle cyclone
- filtration at 550 ^oC by using ceramic fibre filters of Madison Filter, no need for special sorbents
- catalytic decomposition of tars and ammonia in two-stage catalytic reformer using Zr-monoliths developed in WP1 and commercial nickel catalysts.

The conversion of tars in the two-staged reformer is presented in Figure 8 and the conversion of nitrogen compounds in Figure 9. When the reformer was operated at 890 ^oC, the tar conversion was already almost complete and only some benzene passed through the catalytic conversion reactor. Even the benzene concentration could be further reduced to almost zero by increasing the operation temperature of the reformer to 940 ^oC.

As can be seen from Figure 9, high conversion of ammonia is much more difficult to achieve. At below 900 ^oC, the conversion is clearly less than 50% and even at 940 ^oC approximately 25–30% of ammonia will still pass through the reformer. Evidently higher operation temperatures (of the order of 1 000 ^oC) or larger catalyst volumes would be needed to maximise ammonia conversion. The HCN contents in pressurised fluidised-bed gasification of were rather low already after the gasifier.

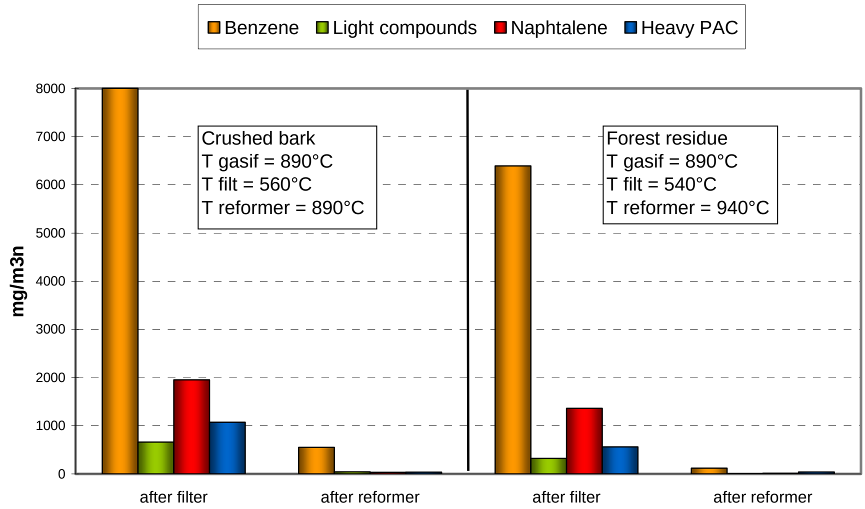

Figure 8. Tar conversion in a two-stage reformer.

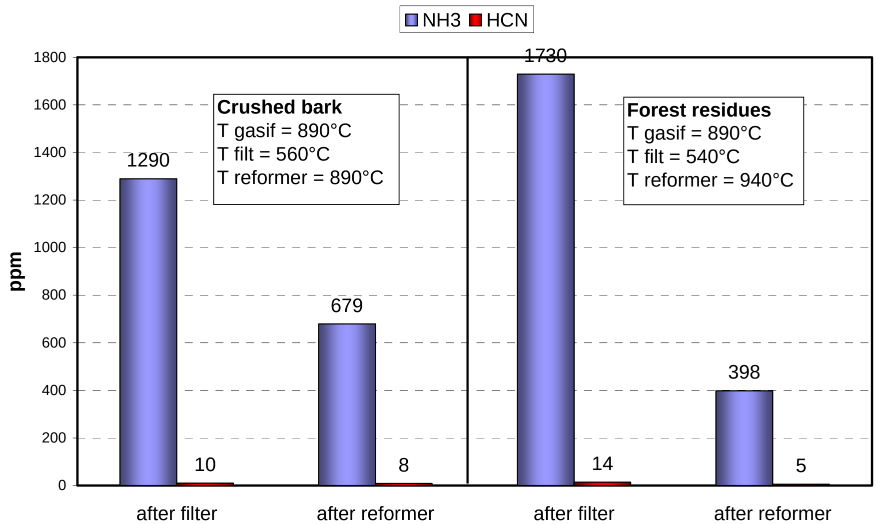

Figure 9. NH3 and HCN conversions in a two-stage reformer.

2.5 WP5 Advanced Gasifier-Engine Plants

The overall aim of WP5 was to study and find means to reduce the specific costs of the power generation unit, which will help to reduce the return of investment time of biomass-to-electricity plant. Another important aim was to develop efficient and cost-effective emission control technologies.

Detailed objectives were

- to improve engine performance and to reduce specific investment cost by 15%
- to design gasifier-engine concepts for 1–10 MWe with biomass-to-electricity efficiency 35–40% and investment cost of 2 000–2 500 €/kWe
- to develop near-zero emission gasifier-engine power plant process concepts with respect to CO, hydrocarbon and NO_x emissions.

These objectives were approached by carrying out extensive R&D activities mainly by GEJ. In addition, part of the work was carried out in Güssing, where BKG assisted GEJ. In addition, Repotec & TUV and VTT & Kokemäen Kaasutin were also co-operating with GEJ in designing optimal gasifier-engine concepts based on their gasification processes.

GE Energy's Jenbacher gas engine business is one of the world's leading manufacturers of gas-fuelled reciprocating engines, packaged generator sets and cogeneration units for power generation.

The gas engines range in power from 0.25 to 4 MW and run on either natural gas or a variety of other gases (e.g., biogas, landfill gas, coal mine gas, sewage gas, combustible industrial waste gases and pyrolysis gas as well).

<u>Improved engine performance and reduced specific investment cost</u>
<u>Exhaust gas emissions</u>

To ensure that the engines maintain constant NOx and/or CO emissions even with fluctuating gas quality, they must be operated with different parameters for different gas compositions. This is named as gas type 1–2 mode. Variable gas quality due to fluctuating gas composition and the resulting fluctuating calorific value mainly occur with non natural gases. Gas type 1 and 2 are indicators for the available gas quality at the inlet of the gas engine. Gas type 1–2 is an "intermediate" gas type equivalent to the gas currently being used. For instance the CH_4 content (also CO, H_2 or similar gas compounds can be used) will be somewhere between the contents of gas type 1 and 2. All the engine parameters for this gas are calculated from the data entered for gas types 1 and 2 and cannot be entered directly or displayed on the visualisation unit.

The calculation of the parameters for gas 1–2 requires the availability of a control gas-quality signal, e.g. CH_4 signal. If an operation involving another gas (e.g. pure natural gas) is provided in parallel to the operation in gas type 1–2, the settings for this other gas are implemented in gas type 3. If the gas of fluctuating quality and this other gas are mixed, the result will be a mixed operation between gas type 1–2 and gas type 3. All these adjustments of engine parameters are initiated automatically by the engine control system and provide the possibility for stable exhaust gas emissions.

Plant modification

As in the topic above intercooler blocking is a result of condensation. A further possibility to avoid this procedure is an optimisation of the boundary conditions. This means a prevention measure to undercut the dew point of the fuel gas. The main affected place at a gas engine is the gas mixing system, were the gas is mixed with air. This procedure made it necessary to make several adjustments at running engine plants operating with non natural gas. A newly designed gas filter system, preheated and insulated gas train and a warm up system for the engine intake air were installed in the field (Figure 12).


Figure 10. With tar blocked engine parts.

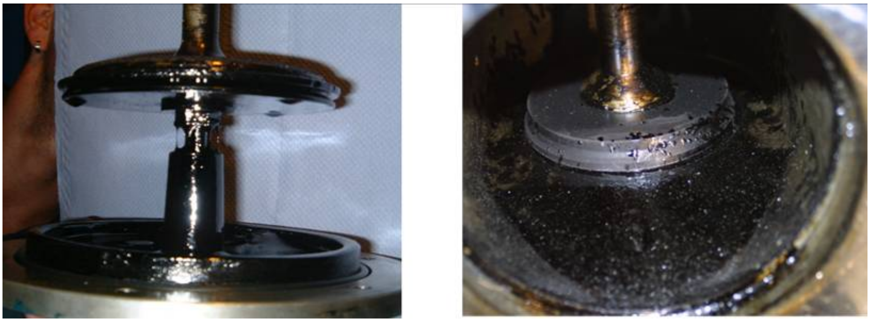

Figure 11. With tar blocked parts of the gas train.

Figure 12. Adjusted gas train and preheated engine inlet air.

Combustion

The combustion of H_2-rich gases, as wood gas or the like, can be critical on gas engines regarding to knocking and auto ignition. The high content of H_2, CO and quality fluctuations at the raw gas may lead to these both events. In addition to power output fluctuations this may result in unwanted phenomena causing damages on the gas engine as illustrated in Figure 13 and 14.

Figure 13. Damage on inlet valve at cylinder head.

Figure 14. Damage on piston.

GE Energy with its Jenbacher gas engines developed a new detection system in combination with the ignition system. The main function of this system is that several combustion parameters were sent to the engine control system. This sensor detects each small, unusual change at the combustion chamber. This makes it possible to change the significant engine parameters to prevent damages on the engine, immediately.

To improve the engine performance and to reduce costs BKG worked together with GE Energy on mainly the following issues:

- Lubricating oil: With the new type of oil the knocking of the engine could be nearly totally decreased. BKG still took every 250 hours an oil sample for analysis. The operating time couldn't be increased. So for this after 40 000 hours at the engine BKG would try another type off lubricating oil. These tests will be accomplished in summer 2009.
- Ignition system: With the new ignition system the ignition point can be changed at each cylinder. So when one cylinder knocks the engine has not to

decrease the load of all cylinders and by that the whole power of the engine. This ignition system measures also the noise of the valves at the cylinder. That should also help to see possible problems in advance and should increase the operation hours. The system is working very well at the moment.

- Intercooler: BKG tested a new type of intercooler which should be more resistant against corrosion and which can be cleaned easily. BKG mounted the new cooler and measured different values to appoint the actual status of the cooler.

The design of the optimised engine power plant based on the dual fluidised bed gasification process was developed by TUV and Repotec. VTT and Kokemäen Kaasutin made similarly design basis and performance evaluation for the gasifier-engine plants based on Novel fixed-bed gasifier.

Conclusion

Based on the results of the EU Big Power project, GE Energy's Jenbacher special gas portfolio could be extended in case of engine power output and engine availability. Finally it can be seen that the special gas segment is increasing and will increase further in the future. GE Energy will follow up its development program in gas usage of non natural gases and special gases for its Jenbacher gas engines and continue to invest in research and development resources in the future.

2.6 WP6 BIG-FC-system development

The objectives of WP6 were to create design basis for high efficiency power and heat production systems based on advanced biomass gasification and optimised MCFC system aiming

- to create an optimised MCFC design basis and performance analysis both for air-blown and steam gasification gas
- to achieve technical readiness for pilot testing in ca. 250 kW HotModule scale
- to design gasifier-MCFC concept for 0.5–5 MWe with 40–50% eff. and 2 500–3 000 €/kWe.

In the beginning of the project, a system simulation tool for the HotModule system using different types of gases was developed by MTU. Then the system designs of three wood gas fed HotModule plants were developed and elaborated. They were based on data delivered by other project participants or by a third party. For these three applications a full basic system design and a complete set of design data have been developed. Cost estimations have been elaborated for different HotModules. Description of different Gasification – MCFC Plants using different HotModules was prepared and design readiness for industrial-scale piloting or demonstration was achieved.

System performance

Based on the results of investigations performed with system simulation tool and under consideration of data concerning gasification systems contributed by other project partners three system designs of HotModule units adapted to different gasification systems were developed and investigated. They were optimized for the Güssing average gas (allothermal), the nitrogen reduced Kokemäki gas (autothermal) and the hse-woodgas (allothermal). For these three applications a full basic system design and a complete set of design data have been developed.

A general plant layout is given in Figure 15 and the final results for performance of the HotModule systems with different wood gases is shown in Table 5.

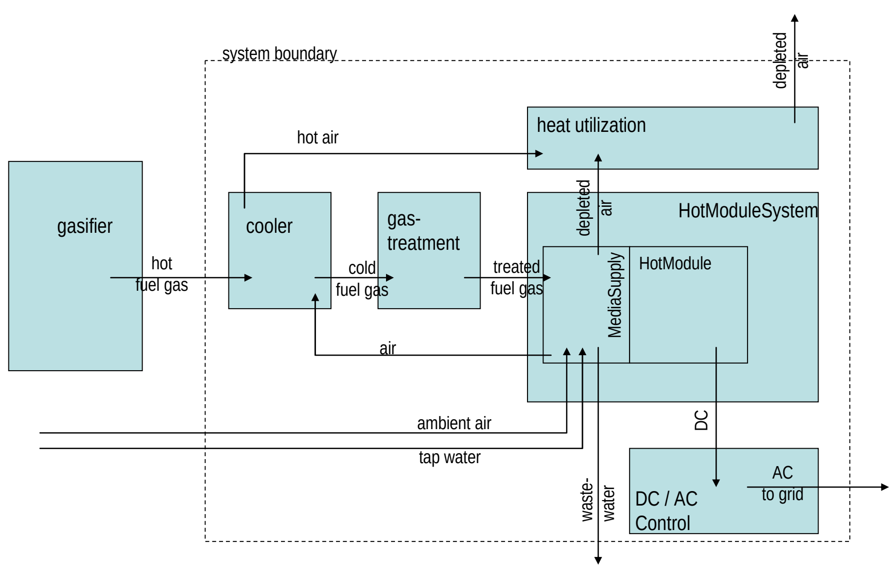

Figure 15. General design of wood gas fed HotModule Plant.

Table 5. Basic data of different gasification-HotModule Systems.

Gasification plants with different HotModules		HM 300	HM 310	HM 320 2008	HM 320 2010	3 x HM 320 2010
electrical efficiency, syngas, calculated	Güssing	41.1%	41.1%	41.1%	41.1%	41.1%
	Kokemäki	39.2%	39.2%	39.2%	39.2%	39.2%
	hse	41.4%	41.4%	41.4%	41.4%	41.4%
electric power to grid (kW el)	Güssing	246.5	295.8	340.2	340.2	1020.5
	Kokemäki	213.9	256.7	295.2	295.2	885.5
	hse	249.1	298.9	343.8	343.8	1031.3
heat performance incl. feedgas cooler	Güssing	291.9	350.3	402.8	402.8	1208.5
	Kokemäki	276.9	332.3	382.1	382.1	1146.4
	hse	273.2	327.8	377.0	377.0	1131.0
input gasflow (kW)	Güssing	599.8	719.7	827.7	827.7	2483.0
	Kokemäki	545.7	654.8	753.0	753.0	2259.0
	hse	601.7	722.0	830.3	830.3	2491.0
input gasflow (Nm3/h)	Güssing	162.1	194.5	223.7	223.7	671.1
	Kokemäki	242.5	291.0	334.7	334.7	1004.0
	hse	154.3	185.1	212.9	212.9	638.7

Cost estimation

Cost estimations were elaborated for different HotModules and due to many development activities under the umbrella of commercialization of the fuel cell technology at MTU Onsite Energy, which are outside of this project, the economical investigations were performed on the basis of the HotModule 310 and HotModules 320 to be delivered 2009 respectively 2010 because HM300 is not longer available. The HM 320 has more cells and is rated to a nominal capacity of 300 kW net performances approximately. It will specifically cheaper than the present HotModule HM300. The cost estimations are based on budgetary offers of MTU Onsite Energy GmbH, dated on 16.11.2007 and updated later.

In order to allow an economical evaluation, the specific costs of electricity for each of the mentioned plants have been calculated under the following assumptions:

- plant lifetime — 16 a
- stack lifetime — 4 a
- annual operational hours — 8 000 hrs/a
- inflation rate — 3%
- interest rate for loans — 5%.

With these figures the dependence of the Cost of Electricity (COE) from the fuel input price (FP) (price of the gas from gasifier downstream gas cleanup system) and obtainable revenue for usable heat (HR) was calculated.

The results can be given in the following equations:

HM 310 in 2008: COE (€/kWh) = 0,1305 (€/kWh) + FP (€/kWh) * 2,940 – HR (€/kWh) * 0,850
HM 320 in 2009: COE (€/kWh) = 0,1088 (€/kWh) + FP (€/kWh) * 3,195 – HR (€/kWh) * 0,845
HM 320 in 2010: COE (€/kWh) = 0,0861 (€/kWh) + FP (€/kWh) * 3,195 – HR (€/kWh) * 0,845

The range of valid values for the fuel price (FP) is 0 to 0,5 €/kWh. The range of valid values for the revenues for useable heat (HR) is 0 to 0,15 €/kWh.

COE (FP=0; HR=0) depends mainly from Investment costs of HotModule and lifetimes and other economical data, whereas the factors beside FP and HR are depending on efficiency and heat to power ratio mainly.

Costs of electricity using a HotModule 320 delivered in 2009 will be 10,88 cts/kWh under the precondition of the above mentioned input parameters and for free feed gas and no revenues for heat. If you assume a feed gas price of 15 cts/kWh at the interface point to the HotModule and additional revenues for utilized heat with 3 cts/kWh, the resulting COE will be 56 cts/kWh. With these costs an economical operation of such plant seems not to be possible. A competitive operation will be possible for fuel prices lower than 5 cts/kWh and heat revenues in the same range: COE will be under these conditions 12 cts/kWh.

Based on the positive results of the investigations within the present project concerning the usability of wood gas as a feed for fuel cell HotModules MTU Onsite Energy recommends to build up demonstrators for that combined technologies at the Güssing gasifier and together with a hse-gasifier in order to verify the resulting efficiencies, which will be much higher than that of conventional prime movers like piston engines, small gas turbines and others

2.7 WP7 Case studies and techno-economic assessment

The most promising biomass-to-power concepts have been defined and evaluated during the final reporting period of the project. Necessary input data was collected in respect to Finnish, Austrian and Greek conditions and techno-economic case studies have been carried out. Interesting economically attractive applications for the BiGPower technologies could be found in all three target countries and suggestions for demonstration projects were also made.

2.7.1 Finnish case studies

The Finnish case studies were focused on new power production concepts based on advanced pressurised gasification. The case studies were carried out by Carbona and the following applications were included in the studies:

- new biomass IGCC as a stand-alone CHP plant
- biomass IGCC retrofit to and existing natural gas fired combined cycle CHP plant
- biomass IGCC as a compound cycle with and existing large condensing power plant using coal as the main feedstock
- advanced biomass gasification-engine (BGGE) concept.

In the studies of WP4, Carbona found out that there are only very few gas turbines suitable to LHV gas firing. As the economy of the smaller machine in 10 MWe scale in Finnish conditions (/with low price of electricity and low level of renewable electricity subsidy) is rather poor, the detailed studies were focused on the larger gas turbine in 40 MWe class (Ge Frame 6B).

The first process concept was a new large-scale combined heat and power production plant designed around GE Frame 6B gas turbine and Carbona's gasification technology. This process concept was estimated to have the following performance during heating season:

- biomass feed rate: 14,7 kg/s at 40% moisture, 156,58 MJ/s
- power production by GT: 47,51 MW
- power production by ST: 20,40 MW
- total net power production: 62,86 MWe
- district heat supply: 67,1 MJ/s
- power generation efficiency: 40,1%
- total efficiency: 83,0%.

During war season when only small amount of heat was produced the power generation efficiency was estimated to be 45,8% with a total efficiency of 51,3%. The total investment costs of this plant were estimated to 84,7 M€ corresponding to 1 350 €/KW_{net}.

The second process concept was designed around and existing natural gas fired GE Frame 6B based combined cycle CHP plant. This plant is producing process steam for neighbouring industrial clients as well as district heat for local heating network. In the techno-economic studies the operational statistics (e.g. heat demand) from a typical operating year were used as the basis and the economy of the plant modification was estimated by comparing the IGCC modification with the performance of the original natural gas fired power plant. In the basic design the total electricity production of the power plant increased from the original 51,6 MWe to 59,7 MW with the same heat production. Power efficiency was increased from 37,4% to 38,6% when the efficiency is calculated based on the LHV of the biomass before fuel drying. Total efficiency to power and heat was slightly decreased from 67,9 to 66,0%. The estimated total investment costs were 45,3 M€.

The third process alternative was designed around an existing large-scale coal fired power plant which is used as condensing power plant without district heat production. The power plant is a 169 MW_e steam power plant designed for base load operation. At this plant the capacity of Frame 6B GT is about ¼ of the steam turbine capacity, which allows designing the plant with optimal integration. The performance of the new compound cycle plant was then compared to that of the original fossil fuel power plant. Main conclusions were as follows:

- Renewable fuel share of total fuel input was 29,6%.
- Net power production capacity was increased from 162 MWe to 230,2 MWe.
- Total efficiency was increased from 43,0% to 44,3%.
- Investment costs 74,6 M€ corresponding to 1 100 €/kWe.

Finally Carbona also evaluated an advanced gas engine plant, which is based on injecting warn filtered product gas from pressurised gasification directly into a gas engine. This concept, however, requires substantial development from the engine manufacture. The results of the preliminary evaluation of this concept were as follows:

- fuel feed rate to the dryer: 1,71 kg/s corresponding to 18,177 MJ/s
- net power production: 5,45 MWe
- district heating capacity: 7,96 MJ/s
- electric efficiency: 30,0%
- total efficiency: 82,4%

– total investment costs (preliminary estimation): 17,95 M€ corresponding to 3 293 €/kWe.

The economic feasibility of these four processes was estimated in typical Finnish boundary conditions illustrated in Table 6.

Table 6. Cost evaluation basis used in Finnish case studies.

Price of biomass	€/MWh	15
Price of electricity	€/MWh	45
Feed-in tariff subsidy	€/MWh	6.9 *)
Price of heat	€/MWh	35
Annual labour costs per person	€/a	35 000
Investment support	% of investment	30 (demo) *)
Annuity factor	10%, 15 a	0.132
Annual full power operation time	h/a h/a	7 000 5 500

*) availability to be discussed with authorities for power generation capacity class > 10 MWe

The techno-economic studies very clearly showed that under the Finnish economic conditions, only combined heat and power concepts based on advanced gasification can be economically attractive. Both the green field biomass IGCC plant and the replacements of natural gas by biomass gasification in an existing combined cycle plant seemed to be economically very interesting. The integration of biomass gasification and gas turbine cycle to a large condensing coal-fired power plant was economically not interesting. The smaller size plant based on advanced gas engine was not competitive and would require much more renewable electricity subsidies than is the present case in Finland.

As a final conclusion drawn from Finish case studies it was suggested to launch a real biomass-IGCC demonstration project on CHP application based on the well-proven GER Frame 6B gas turbine. A successful demonstration of this technology in economically attractive scale would strongly push forward also the development of other gas turbines thus enabling realisation of biomass IGCC also in other size classes.

2.7.2 Austrian case studies

The Austrian situation can be characterised by limited biomass (wood) resources, need for district heating, but mainly within small existing heating nets and a preferred feed in tariff for green electricity.

Due to the high value of electricity compared to the value of heat the technology has to be optimised for the electrical output. As the price of wood is relatively high, a high efficiency, which means a low consumption of wood, is of a high relevance and can justify some increase of investment costs. The chosen technology was the Next Generation Power Plant based on Dual Fluid Bed gasifier and gas engine developed in WP2 and WP5.

Based on the operational analysis of the Güssing plant, the following aspects of optimisation were considered for the next generation power plant:

- A high biomass water content has a negative influence on the plant's efficiency and performance. Therefore, appropriate steps have to be taken in order to keep the water content of the biomass entering the gasifier below 20 wt-%. A feasible method would be an integrated biomass dryer based on low temperature residual heat. Possible heat sources are 1) RME-cooling before the tar scrubber unit and 2) lowering the temperature of the district heat return flow before gas engine. The plant's overall efficiency can be significantly increased through integrated biomass drying.
- The high temperature heat resulting from the hot gas (producer gas, flue gas and exhaust gas) cooling section could be used for electricity production, the residual heat still be used for district heating. As a consequence, the overall exergy conversion efficiency could be increased. Thermo oil could work as a heat carrier for the mid temperature heat, providing the necessary energy for a closed cycle. Because of the compact construction and the high adaptability to various temperature levels, an ORC (Organic Rankine Cycle) would be well suited. An increased overall electricity production is generally associated with a higher economic efficiency of the power plant.

Figure 16 shows the process flow sheet of the next generation CHP.

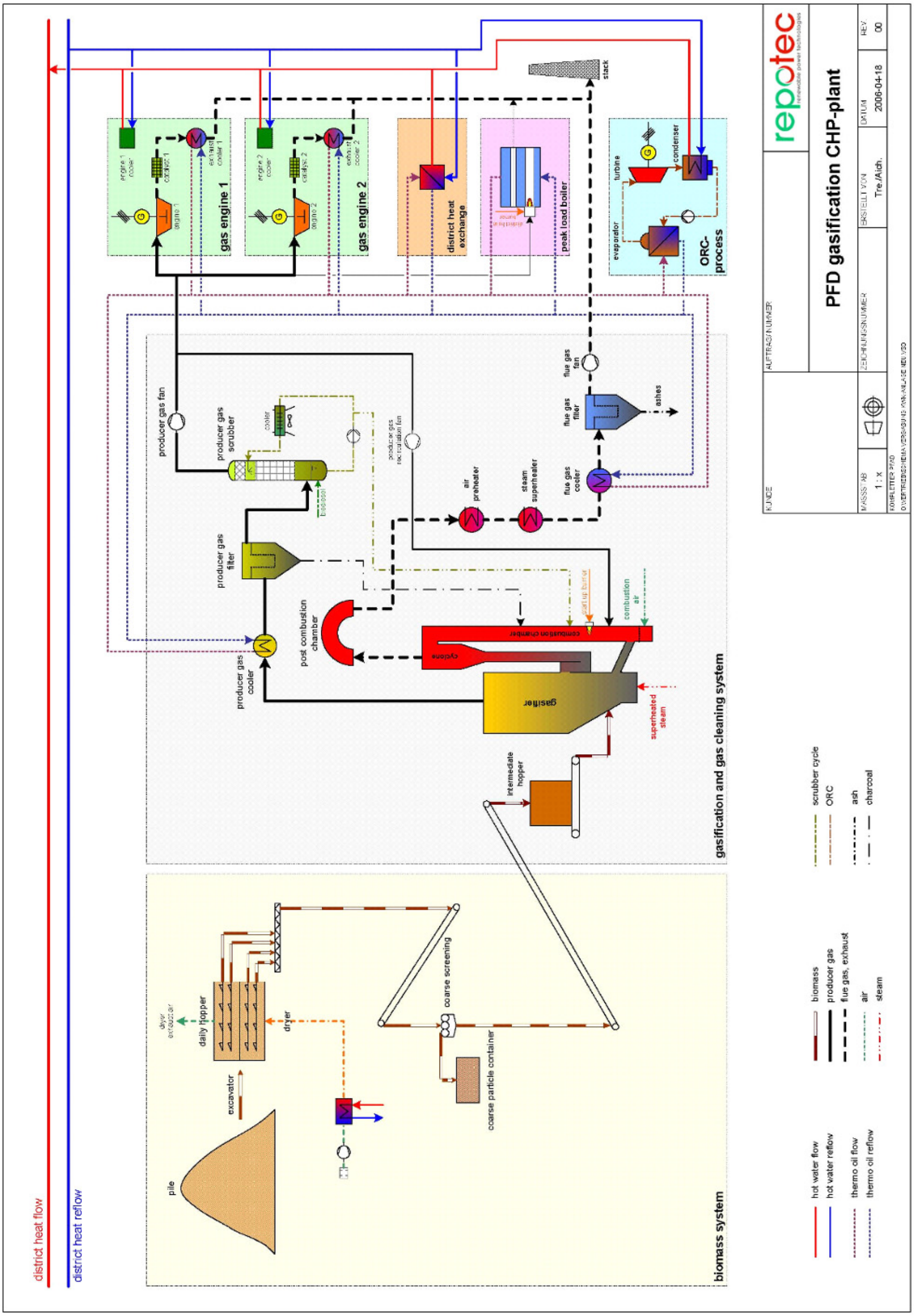

Figure 16. Flow sheet of the next generation power plant.

As stated before the realisation of the CHP plant in Güssing in the year 2000 marked a breakthrough for the application of biomass gasification for commercial CHP systems. The initial investment was app. 9 000 000 € for the turn key erection. With an electrical output of 1960 kW (gross) the specific investment was app. 4 600 €/kWel. Due to the Austrian "Ökostromgesetz", a law, granting a preferred feed in tariff for green electricity, and some direct subsidies, the plant has been successfully operated since 2002.

Unfortunately prices for steel and metals and subsequently also the prices for power plant equipment and -machines showed a dramatic raise. A new plant following the improved concept, including fuel drying and ORC cycle, would cost app. 22 000 000 € for a plant with an electric output of 4 500 kW (gross), which gives a specific investment of app. 4 900 €. Furthermore the subsidies for the heat relevant parts can be deducted from the overall investment, resulting in a total of 19 500 000 €.

The economic studies carried out by Repotec led to the following overall conclusions: On the cost side the biomass fuel and the investment costs have the highest relevance. Almost as relevant as the overall investment are the interest rates. Widening the fuel spectrum in order to make cheaper biomass applicable for the process and a simplification of the process in order to reduce the investment costs have been logical key issues of the research project. The optimised process resulting out of the project shows a good profitability under the Austrian frame conditions.

2.7.3 Greek case studies

The aim of the Greek case study was to identify potential attractive locations in Greece for application of biomass-to-power systems and to select the most suitable BiGPower process concept for potential application in each case. The optimal plant designs defined in WP2-WP6 were used as starting point for selecting the respective process concepts. Overall, the most promising process alternatives were evaluated in selected potential Greek cases. The study included evaluation of the technical performances and economic competitiveness of the selected cases.

As an initial step, an effort was made to estimate the biomass capacity of various candidate regions in the Greek territory, since biomass projects are site- and fuel-specific. After assessing the biomass potential of each candidate region and evaluating the special characteristics of each process concept, three cases were qualified to be included in this case study:

1. The case of Grevena for application of stand-alone Biomass Gasification Combined Cycle (BGCC) with maximum capacity of 17.8 MWe, based on GE10 gas turbine and pressurised gasification.
2. The case of Ptolemaida – Kozani region for application of parallel integration of a 17.5 MW_e Gasifier / Gas Turbine system with an existing lignite-fired power plant (Agios Dimitrios, Unit III 315 MWe) based on SGT-500 gas turbine.
3. The case of Crete Island for application of a Biomass Gasification Gas Engine (BGGE) generic CHP concept with 8 MWe capacity.

The major data and figures derived from the techno-economic evaluation of the three cases are summarised in the following Table 7.

Table 7. Summary results of the techno-economic evaluation.

	Grevena Case 1	**Ptolemaida-Kozani Case 2**	**Crete Island Case 3**
Process Concept	BGCC based on air-blown pressurized gasification and GE10 GT	Parallel integration of GT/gasifier system with an existing lignite-fired Unit (315 MW_e) based on air-blown pressurized gasification and SGT-500 GT.	Generic BGGE process scheme
Power Output (MW_e)	17.8	17.5	8 (15–20 MW_{th})
Net Electric Efficiency	37.8%	37.1%	26%
SIC (€/kW_e)	3 870	2 194	1 800–2 500
COE (€/kWh)	0.110	0.081	0.125

Case 1: Grevena District

Grevena presents an excellent biomass capacity of wood origin due to the presence of vast forest areas and wood industry. Therefore a stand-alone BGCC system was examined based on commercially available GE10 GT (11.8 MW_e output). Modelling activities resulted in satisfactory efficiency of up to 37.8%, reflecting current status of this kind of technology. Commercial availability of reliable and efficient GT within the power range of 10–40 MW_e modified for hot syngas operation is the key–element for the successful commercial breakthrough of BGCCs.

Economic evaluation on SIC and COE basis was not promising, validating the fact that BGCC's are still affected by economies of scale. Size of BGCC plants is still confined by biomass availability and logistics and larger size of plant would be in danger. Minimum size for economic competitiveness under Greek retail electricity prices was to around 70 MW_e. This is considered a very risky investment scheme to follow, even if the last attractive feed-in tariffs (75.82 €/MW_e) and subsidies (up to 40%) of Law 3468/2006 [30] were applied. BGCC technology must be further demonstrated and is believed that after the 10^{th} plant has been installed, the costs will become attractive due to learning effects, even in the small to medium scale examined in this concept.

Case 2: Ptolemaida-Kozani District

This region is the power centre of Greece and has a satisfactory biomass potential. It is a neighbouring region to Grevena, since both belong to Western Macedonia Prefecture and potential biomass logistic chain could be fed from both Districts. The novel process of a gasifier/GT system integrated with an existing lignite-fired unit (315 MWe) was examined. The system has an efficiency of up to 37.1% based on SGT-500 GT (not modified to working on LCV gas) and is integrated with the existing steam cycle by setting an economizer downstream the GT for feedwater preheating of the steam cycle. It is considered a novel scheme that results in lower CO_2 emission of the whole power block due to fossil energy savings.

Economics are favourable due to the absence of the steam cycle. Only the gasifier, gas cleaning step, GT and heat exchangers are needed to set up the additional power block. Very competitive SIC and COE figures were obtained. Moreover, for a price of CO_2 allowances of 20 €/ton the COE of the parallel combined cycle becomes equal to the cost of the lignite-fired unit, according to sensitivity analysis of the CO_2 price on the COE of the compound cycle. This was done to examine the environment benefits on cost basis. The Public Power Corporation should also examine this process route, apart from conventional co-firing which is under way in cooperation with CERTH.

Case 3: Crete Island

Crete is a very attractive region for distributed/decentralized power generation, because it is not interconnected to the main electricity grid. There is also an excellent biomass capacity due to expanded agriculture activity and olive oil industry, especially in Heraklion District. BGGE process concept was selected in the size range of 8 MWe. It was assumed that every concept from the existing demonstration activities (Kokemaki and Güssing), as well as other concepts proposed by BigPower partners are suitable for application to Crete's biomass fuel types. The concept will be feasible only on operating on CHP mode, producing about 15–20 MW_{th} to cover heat demands.

SIC was quite acceptable when calculated after escalation based on actual plant costs of the existing demonstration projects but it was attractive when solely based on literature surveys. The last feed-in price and subsidy (40%) given by the Greek government should definitely help the project to become competitive and help potential investors.

3. Publishable results

The following publishable results have been generated among participants of BIGPOWER project:

Scientific papers

Rönkkönen, H.; Simell, Pekka; Reinikainen, Matti; Krause, O. 2009. The Effect of Sulfur on ZrO2-Based Biomass Gasification Gas Clean-Up Catalysts. Topics in Catalysis, vol. 52, (2009), pp. 1070–1078. doi:10.1007/s11244-009-9255-8.

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P. Klimantos, N. Koukouzas, A. Katsiadakis and E. Kakaras, Air-blown Biomass Gasification Combined Cycles (BGCC): System Analysis and Economic Assessment. Energy, Volume 34, Issue 5, May 2009, pp. 708–714. doi:10.1016/j.energy.2008.04.009.

Viinikainen, Tiia; Rönkkönen, Hanne; Bradshaw, Heather; Stephenson, Hazel; Airaksinen, Sanna; Reinikainen, Matti; Simell, Pekka; Krause, Outi. 2009. Acidic and basic surface sites of zirconia-based biomass gasification gas clean-up catalysts. Applied Catalysis A: General, vol. 362, 1–2, pp. 169–177. doi:10.1016/j.apcata.2009.04.037.

Conference presentations

Hannula, I.; Simell, P.; Kurkela, E.; Luoma P.; Työppönen T.; Haavisto, I.; Lappi K. 2008. Waste water recycling and NOx emissions of the Novel Kokemäki CHP plant. Proc. of the 16th European Biomass and Exhibition Conference 2008, pp. 869–870.

Aichernig, C., Hofbauer, H., Pfeifer, C., Rauch, R. Biomass Gasification CHP Plant Güssing: Research Centre for 2nd Generation Biofuels. Oral Presentation. Proc. of the 16th European Biomass and Exhibition Conference 2008, p. 731.

Kreuzeder A., Pfeifer C., Hofbauer H. Fluid-dynamic investigations in a cold model for a dual fluidized bed biomass steam gasifier: solids circulation and fuel residence time. 9th International Conference on Circulating Fluidized Beds, Hamburg, Germany, May 2008. Book of abstracts.

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Christoph Pfeifer, Hermann Hofbauer, Tim Schulzke, Christoph Unger. Catalytic tar removal in a secondary slip-stream reactor at the biomass CHP in Guessing, Austria. Gas Cleaning at High Temperatures 7, Newcastle, Australia, June 2008. Book of abstracts.

Solla, Anu; Simell, Pekka; Reinikainen, Matti; Rönkkönen, Hanne; Krause, Outi; Bradshaw, Heather; Stephenson, Hazel; Monks, Gary. 2007. Development of zirconia catalysts for hot gas cleanup. European Catalysis Conference - Europacat VIII. Turku, Finland, 26–31 August 2007. University of Turku. Oral presentation.

Hannula, Ilkka; Lappi, K.; Simell, Pekka; Kurkela, Esa; Luoma, Pertti; Haavisto, I.. 2007. High Efficiency Biomass to Power Operation Experiences and Economical Aspects of the Novel Gasification Process. 15th European Biomass Conference and Exhibition, from Research to Market Deployment. Berlin 2007. Book of abstracts.

C. Jünger, A. Kreuzeder, G. Soukup, C. Pfeifer, H. Hofbauer. Drying of biomass – Influence of the fuel water content on the dual fluidized bed steam gasification process. Success & Visions for Bioenergy, European workshop on thermal processing of biomass for bioenergy, biofuels and bioproducts, Salzburg, Austria, 22–23 March 2007.

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P. Klimantos. Advanced Biomass Gasification Systems for Power Generation, 10th November 2007, Workshop: Sustainable Development in Thrace, Organized in the framework of EC Initiative INTERREG III A, Workshop held in the framework of the 1st Pan-Hellenic Energy Exhibition "Energon 2007" organized by Thessaloniki International Fair S.A., 8–11 November, 2007, Komotini, Greece.

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Thesis

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Master's Thesis: Isabella Aigner. Einfluss des Brennstoffwassergehalts auf den Betrieb eines Zweibettwirbelschichtvergasers, Vienna University of Technology, Institute of Chemical Engineering, 2008 (in German).

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Master's Thesis: Harald Frey. Brennstoffvariation bei der Zweibett-Wirbelschicht-Dampfvergasung, Vienna University of Technology, Institute of Chemical Engineering, 2007 (in German).

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Publishable Final Activity Report of BiGPower Project

Abstract

The BiGPower project was related to the development of 2nd generation high-efficiency biomass-to-electricity technologies, which have the potential to meet the targets of cost effective electricity production from wide range of biomass and waste fuels in size ranges typical to locally available feedstock sources (below 100 MW_e). This project was designed to create the fundamental and technical basis for successful future industrial developments and demonstration projects aiming to commercial breakthrough by 2010–2020. This overall aim was approached by carrying out in pre-competitive manner well-focused R&D activities on the key bottlenecks of advanced biomass gasification power systems.

Three promising European gasification technologies in this target size range were selected to form the basis for the development: 1) air-blow novel fixed-bed gasifier for size range of 0.5-5 MWe, 2) steam gasification in a dual-fluidised-bed gasifier for 5–50 MWe and 3) air-blown pressurised fluidised-bed gasification technology for 5–100 MWe.

In all biomass gasification processes, the product gas contains several types of gas contaminants, which have to be efficiently removed before utilising the gas in advanced power systems. The key technical solutions developed in the BiGPower project were: a) high-temperature catalytic removal of tars and ammonia by new catalytic methods, and b) development of innovative low cost gas filtration. Three most potential power production cycle alternatives were examined and developed: 1) gas engines, 2) molten carbonate fuel cells (MCFC) and 3) the simplified Integrated Gasification Combined Cycle (IGCC) process. The performance and techno-economic feasibility of these advanced gasification-to-power concepts were examined by carrying out case studies in different European Union.

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