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Bio-SNG – Demonstration of the production and utilization  
of synthetic natural gas (SNG) from solid biofuels  
Specific Targeted Research or Innovation Project

## D 1.4 FINAL PROJECT REPORT

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## TABLE OF CONTENT

Table of content .....	II
List of abbreviations .....	III
1 Project execution .....	1
1.1 Publishable summary .....	1
1.2 Technology and performance .....	7
1.3 Specific results from gasification and methanation.....	15
1.4 Use of Bio-SNG in the mobile sector .....	33
1.5 Technical, economic and environmental analysis .....	35
2 Dissemination and use .....	43
2.1 Exploitable knowledge and its use .....	43
2.2 Dissemination of knowledge .....	44
2.3 Publishable results .....	46
List of figures and tables .....	47

**LIST OF ABBREVIATIONS**

bf	Biomass feedstock
Bio-SNG	Bio Synthetic Natural Gas
CHP	Combined heat and power
CH <sub>4</sub>	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
COSYMA	Catalytic fluidized bed reactor facility
CO <sub>2</sub>	Carbon dioxide
DME	Dimethyl ether
fp	Fuel power
FT	Fischer-Tropsch
GHG	Greenhouse gas emissions
HCl	Hydrogen chloride
HHV	Higher heating value
H <sub>2</sub>	Hydrogen
H <sub>2</sub> O	Water
H <sub>2</sub> S	Hydrogen sulphide
kWh	Kilowatt hour
LHV	Lower heating value
MJ	Mega Joule
MW	Megawatt
NH <sub>3</sub>	Ammonia
Nm <sup>3</sup>	Norm cubic metre
ORC	Organic Rankine Cycle
PAH	Polycyclic aromatic hydrocarbon
PDU	Pilot and demonstration unit
ppm	Parts per million
RED	Renewable energy directive
RME	Rapeseed methylester
sfr	Steam fuel ration
TGA	Thermo gravimetric analysis
th	Thermal
TIC	Total investment costs
TPO	Temperature programmed optimisation
TÜV	Technical inspection association (Technischer Überwachungsverein)
VDI	Association of German engineers (Verein deutscher Ingenieure)
vol. %	Volume percent
wt.	Weight percentage



## 1 PROJECT EXECUTION

### 1.1 Publishable summary

#### 1.1.1 Background

The utilisation of natural gas is of high importance within the European energy system. Intensive activities concerning the substitution of natural gas with so called synthetic natural gas respectively biomethane are currently ongoing based on the objectives in the contexts of climate protection and diversification of supply sources. Therefore, a number of concepts are available. Here, the production of biomethane via thermo-chemical conversion of solid biofuels - so called Bio-SNG - is a favourable addition to the provision of biomethane from bio-chemical conversion routes (biogas). Technologies for the feed-in, the distribution as well as the utilisation of biomethane are market-ready and applied commercially.

The biogas production technology based on anaerobic digestion, wet fermentation of biomass residues (and wastes) as well as from energy crops (e.g. maize silage) is mature. The conversion of biomass into Bio-SNG is not that far developed yet. Currently, biomass gasification based on steam for the production of heat and electricity is successfully demonstrated and market-ready. The European project "Demonstration of the production and utilisation of synthetic natural gas" has started in May 2006 against the background of the required subsequent methanation that was implemented in a pilot stage with a few kW thermal capacity.

#### 1.1.2 Objectives

The objective of the "Bio-SNG"-project was to demonstrate the SNG production from woody biomass in the 1 MW-range using steam gasification, advanced gas cleaning, methanation and gas upgrading as a part of an innovative 8 MW biomass CHP gasification plant and to integrate this Bio-SNG into the existing energy infrastructure (i.e. fuel station for vehicles). To meet the specifications required for the gas utilisation in vehicles or the gas-feeding into an existing natural gas grid, the produced SNG has to be upgraded. With this upgraded renewable gaseous fuel, cars were refuelled. These cars are currently in operation for the purpose of demonstrating the application of Bio-SNG within the transportation sector.

The project assessed the overall provision chain of SNG starting with the biomass supply and ending with the utilization of biomethane, including (i) technical (e.g. overall efficiencies), (ii)

economic (e.g. cost efficiency) and (iii) environmental aspects (e.g. overall primary energy demand, GHG emissions).

Furthermore, effects of the commercial implementation of Bio-SNG into the energy system were examined and can be directly compared with other options (e.g. FT, DME) in order to provide transportation fuel from biomass. Additionally, it is a goal of the project to optimise the entire process chains from the wood up to the running car with the overall goal to develop a market-ready technology. Therefore, the technological readiness of the methanation of syngas and the utilization of the produced biomethane within the transportation sector shall be demonstrated. Finally, the chances and limitations of the Bio-SNG technology within the current and future European energy system shall be assessed.

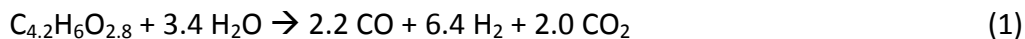
### 1.1.3 Basics characteristics of Bio-SNG

The SNG production is characterised by the possibility that relatively small conversion units with capacities in a range of 10 up to 100 MW<sub>bf</sub> can be used. Hence, the conversion of locally available lignocellulosic biomass into biomethane is possible. The production of synthetic biofuel, electricity and heat (so called tri-generation) allows for high overall efficiencies (e.g. high CO<sub>2</sub> mitigation potential) within the entire production process. In comparison to the production of BtL fuels (like Fischer-Tropsch-fuels), the SNG production system is marked by lower technical and financial risks because of a lower complexity of technology that (e.g. synthesis and fuel treatment). It also works with smaller units. Based on these circumstances, a rapid and easy market entrance is possible. Methane and in this context Bio-SNG has a high market potential and is well known as an energy carrier (transport sector, stationary applications, heat and power) as well as for material utilisation. Within the existing and well developed natural gas grid in Europe, SNG can easily be fed-in and distributed to the final consumer in industry and households. Beside the above mentioned advantages, the combustion properties of methane are already well known and characterised by comparably low emissions.

### 1.1.4 State of the art

The production of SNG can occur within a very promising concept via the steam gasification of woody biomass, gas cleaning, subsequent methanation and a raw SNG up-grading. The steam gasification and the gas cleaning have been demonstrated successfully in a full technical scale (8 MW thermal capacity) at the biomass combined heat and power (CHP) gasification plant in Güssing/Austria. Here, during the last years numerous experiences in the commercial operation were generated. Steam gasification leads to producer gas with a relatively high content of hydrogen and methane as well as a low content of nitrogen. These properties are necessary for an efficient SNG production. Equation (1) describes the production of synthesis

gas from woody biomass. During the gasification process, biomass and water are converted into synthesis gas and carbon dioxide.



The gas cleaning of the producer gas from biomass gasification for application in gas engines and turbines are considered state of the art. In addition to the methanation process, acid components such as  $\text{H}_2\text{S}$ ,  $\text{HCl}$  and organic sulphur that could damage the catalyst have to be removed (e. g. a rapeseed methylester (RME) scrubber). For the conversion of the synthesis gas into biomethane (cf. (2)), a fluidized bed methanation reactor was constructed at the gasification plant in Güssing/Austria during 2007 and 2008. Thus, biomethane can be derived from woody biomass with an overall efficiency of 60 to 65 %.



Besides the production of SNG as a biofuel for the mobile sector, electricity can be generated through the combustion of the raw product gas in a gas engine as well as through the use of rejected heat in the ORC process. The produced heat can be provided for district heating and industry purposes as well.

### 1.1.5 Consortium

The activities in the Bio-SNG project were conducted by a consortium consisting of institutions from Austria, Czech Republic, France, Germany and Switzerland, and the coordination of the entire project was carried out by the German BiomassResearchCentre (DBFZ). The project partners from research and industry are shown in Figure 1.

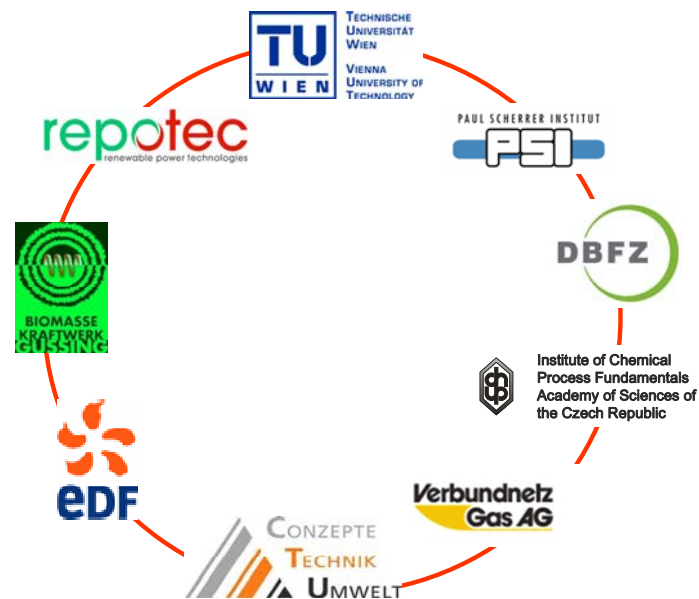


Figure 1: Consortium of the Bio-SNG project

In addition, an advisory board was established. Here, international representatives from the gas industry and associations, from the car industry as well as from environmental organisations provided advice on the future development of Bio-SNG. Moreover, based on the basic analysis of pros and cons of Bio-SNG in the energy market it can be concluded that these pathways seems to be a favourable solution to provide high efficient biomethane in the European and worldwide context.

### 1.1.6 Development and progress of the Bio-SNG project

In the following, an overview on the project development and progress will be given, and major milestones are chosen. For detailed information, please look at [www.bio-sng.com](http://www.bio-sng.com).

The Bio-SNG project started on 01 May 2006. The first meeting of the consortium took place at the University for Technology in Vienna on 25 May 2006. In the following, theoretical as well as practical work in the fields of biomass provision, detailed engineering, gasification and gas cleaning, methanation and gas upgrading as well as process simulation started.

In order to improve the future development and integration of Bio-SNG within the European energy system, the advisory board of the project was founded, consisting of experts from the gas and car industry as well as from environmental and gas associations. During meetings, the pros and cons of this technology were discussed and potential application areas were identified. Furthermore, the required input for promoting the technology was assessed.

Based on the work within the field of gasification and gas cleaning, methanation and gas upgrading as well as detailed engineering, the foundation stone for the Bio-SNG pilot and

demonstration plant was laid out in Güssing/Austria on 08 February 2007. Representatives from national and regional government, industry as well as science came together, emphasizing the importance of the project within the European context.

In the following project phase, the construction of the demonstration plant took place. Numerous obstacles especially in the field of detailed engineering were solved. The overall construction of the plant started with ground inspection in May 2007 and terminated with the end of the mechanical completion phase in June 2008. In the following phase, a number of tests on the electric systems, the singular mechanical equipment and machines as well as on functional groups were carried out in order to guarantee a successful operation of the Bio-SNG plant.

In July 2008, the commissioning started. First test campaigns with gas were performed starting from December 2008. It could be demonstrated that the plant design for the entire process was sound and that the methanation was generally working. In June 2009, after a number of optimisation steps and modifications within the procedure, it was possible to produce Bio-SNG with H-gas quality that could be fed into the fuelling station. Thus, it was possible to demonstrate that the projected objectives of the SNG production could be achieved. The official inauguration of the plant took place on 24 June 2009 in Güssing (cf. Figure 2).



Figure 2: Impressions of the official Bio-SNG plant opening





## Project execution

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Attended by a selected audience from society, industry and government, the project partner provided a short review on the milestones of Bio-SNG project at the inauguration ceremony. Key aspects including the high overall efficiency of the conversion process as well as the favourable economic and environmental dimensions were pointed out. Furthermore, the promising integration of the Bio-SNG technology into the European energy system was highlighted. Representatives from the Austrian Government from both national and local levels outlined the high potential of biomethane produced from wood for mobile and stationary applications. After the official opening by the Austrian Minister for Environment a CNG-car was fuelled with Bio-SNG.

## 1.2 Technology and performance

### 1.2.1 Detailed Engineering

The detailed engineering was split into various activities in order to comply with the nature of such a research and development project in the field of process engineering. This involved some specialities such as communication with the research partners for finding the right basis for the detailed engineering or to create the flexibility required to accommodate the development work, which could not exactly be defined early in the project as it would be required for conventional detail engineering. Furthermore, some input from the ongoing R&D work was integrated into the design during the course of the project such as the results of the work associated with the catalyst testing.

### 1.2.2 Conceptual design

The engineering started with the review of the available process concept. The conceptual design of the plant was developed being based on the R&D needs, the expected operation requirements of the methanation catalyst and the product specifications of pipeline-grade SNG. The different process options were calculated and the most suitable ones were selected. Various parameters had to be fixed such as pressures, temperatures, efficiencies or materials. A special emphasis was all the time that the catalyst shall 'feel well' and that decision taken would allow later for scale up to industrial plant size.

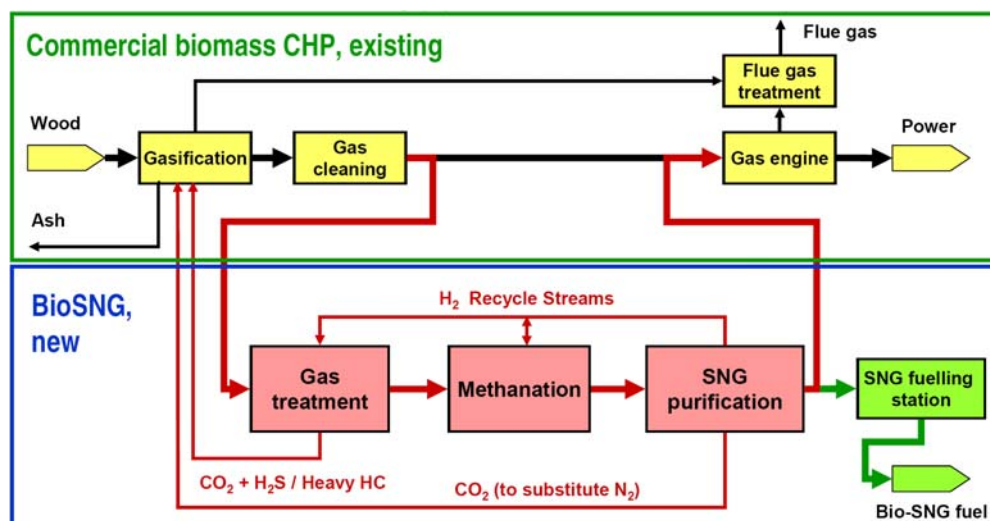


Figure 3: Overall process integration of the new Bio-SNG facility (PDU) into the existing Combined Heat and Power plant (CHP) of the Biomassekraftwerk Güssing GmbH (BKG).

The raw gas is taken after the gas cleaning steps of the existing Combined Heat and Power plant (CHP) of the Biomassekraftwerk Güssing GmbH (BKG). This wood gas, which normally goes to the gas engine, is treated further in order to remove compounds, which could

jeopardize the methanation catalyst i.e. mainly tar and sulphur compounds. The treated gas flows to the methanation, where the raw-SNG is produced by essentially converting CO plus H<sub>2</sub> into CH<sub>4</sub> and CO<sub>2</sub>. The raw-SNG is purified so that the final composition would be suitable to be fed to a natural gas grid. The purified Bio-SNG is lead to the SNG fuelling station or back to Biomasse Kraftwerk Güssing to the gas engine.

### 1.2.3 Process engineering

The process engineering was characterized by iteration and optimization steps. This led to the following process at the end of the basic engineering (cf. Figure 4).

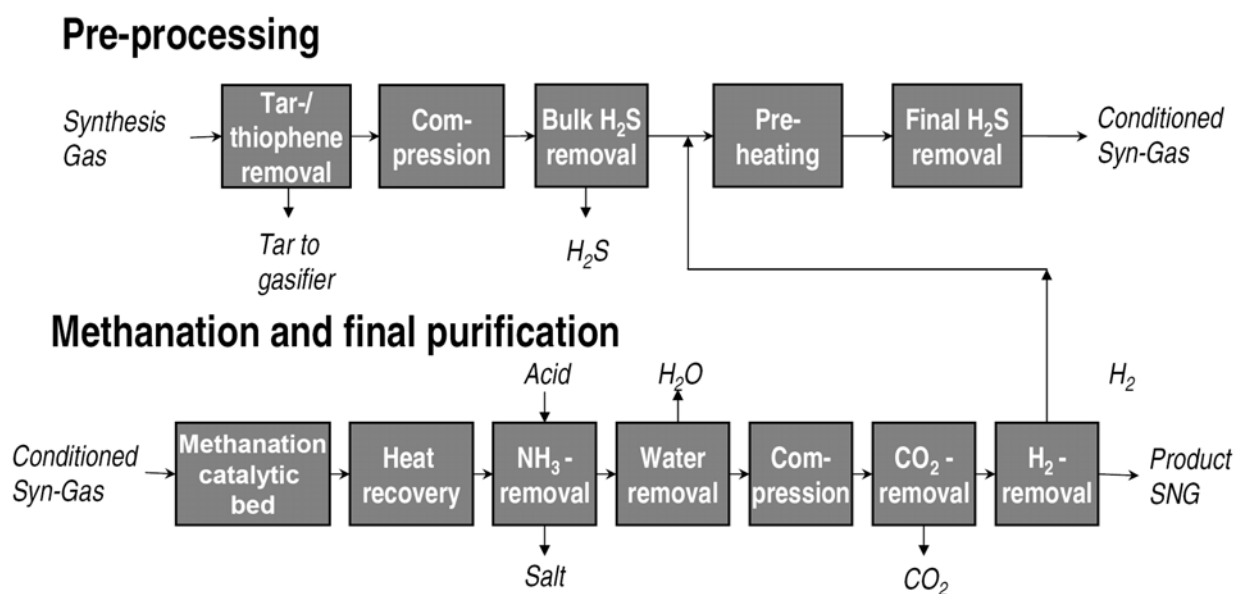


Figure 4: Relevant process steps of the Bio-SNG pilot and demonstration unit.

**Pre-processing:** Tar and sulphur species are removed, the gas is compressed the first time, bulk H<sub>2</sub>S is removed, preheating takes place and the remainder of H<sub>2</sub>S is removed.

**Methanation and final purification:** After the pre-processing, the conditioned synthetic gas is passed to the methanation, where the main reactions take place forming raw-SNG. From that raw-SNG and the methanation reaction itself heat is recuperated, NH<sub>3</sub>, H<sub>2</sub>O, CO<sub>2</sub> and H<sub>2</sub> are removed step by step and to some extent recycled. Furthermore, the gas is compressed. The product leaving these steps is Bio-SNG, which shall fulfil 'pipeline specification'.

The properties of the compounds including equilibrium data had to be put together by literature search and also to some extent by engineering analogy. Rigorous process calculations were required for completing the process engineering. Finally, the heat and mass balances could be derived as an input for subsequent engineering steps.

### 1.2.3.1 Authorial permission

The authorities were contacted early in the design in order to clarify the requirements and the details of the permission procedure for this Pilot and Demonstration Unit (PDU). Environmental aspects were a major issue and it was decided by the authorities that a noise immission analysis (cf. Figure 5) as well as an explosion hazard analysis by TÜV Austria have to be delivered beside the usual documents for the application.

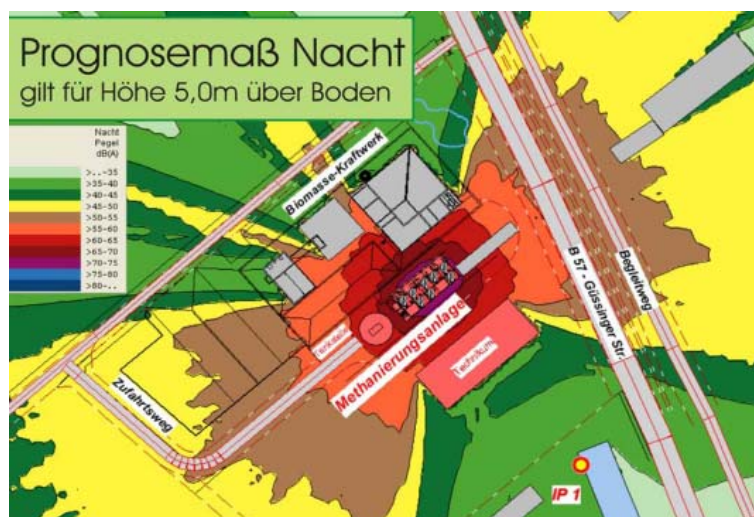


Figure 5: Calculated noise level 5 m above ground during the night; IP 1 refers to the critical residential building.

All the required documents were handed over to the authorities in December 2006. The official hearing took place early 2007 and the building permission was granted subsequently. All other required permissions were granted too.

### 1.2.3.2 Design review

Since the design is based to some extent on new processes, it was decided to review the process and the design in various steps during its development. The design review did not bring radical changes but was a valuable instrument, which forced the process and plant developers to verify their decisions and their handling adequately.

### 1.2.3.3 Equipment design

The equipment design was mainly done by the subcontractors along the line of the prepared specifications. However, some equipment was defined by the industrial partners in detail.

One of those items is the methanation reactor, which is the most critical part in the PDU. The methanation reactor is a fluidized bed reactor, which houses the catalyst. Fluid dynamics, chemical reaction engineering, thermal design, mechanical design and production must fit all

the requirements, which are contradicting to some extent. The methanation reactor is a product of long discussions and certain iteration between PSI (research) and CTU (industry) and finally the manufacturer.

#### 1.2.3.4 Electrical and control design

The electrical and control design needs to comply with the complex requirements of the R&D project too. A computer based control system fulfils the functions of safety control, process control and flexibility.

#### 1.2.3.5 Plant engineering

The process and equipment design flow as an input into the plant engineering. Conceptual lay-outs were produced, which addresses also safety aspects. The concepts were optimized and transformed into the plant layout. Later, this was expanded into a plant and piping layout.

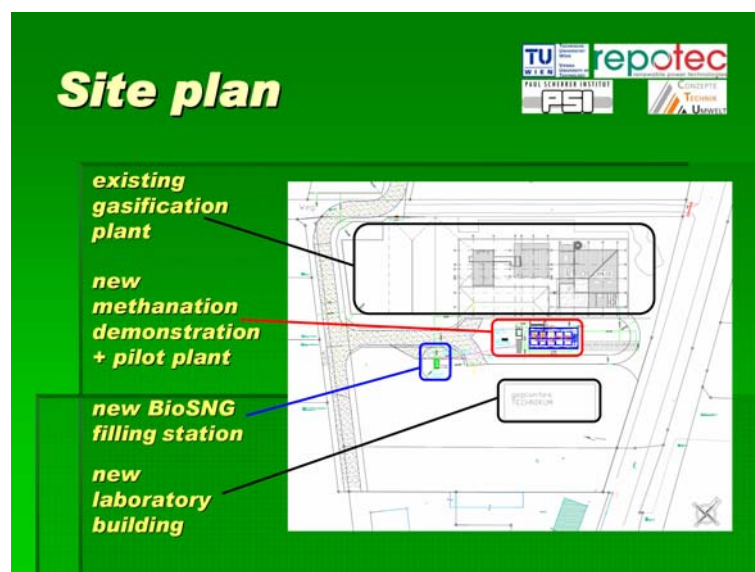


Figure 6: Site plan displaying the integration of the new methanation PDU adjacent to the existing gasification plant. Furthermore, the situation displays the planned new laboratory building and the Bio-SNG filling station

The structural design of the steel structure and the civil engineering followed as well as many other parallel activities.

#### 1.2.3.6 Management

It is obvious that the management of a technically complex project needs a special effort in particular when four partners (i.e. the research partners TUV & PSI; industrial partners

Repotec & CTU) are involved in the engineering. Therefore, an erection consortium was established by these partners, which was lead by CTU.

Various technical, planning and coordination meetings were held between the parties. Furthermore, scheduling and reporting was involved.

#### 1.2.4 Erection and commissioning

The ground preparation work for the fundament of the Bio-SNG unit started in May 2007. The base plate was finished in July 2007 and the erection of the steel construction started. The construction period took until January 2008 and finally the completion of erection could be reached on June 24th, 2008 (cf. Figure 7).



Figure 7: Completion of erection (2008-24-7)

The cold commissioning period between completion of erection and the start of the Bio-SNG production was characterised by checking the mechanical equipment (vessels, pipes, valves, machines, etc.) in accordance to the PID's as well as the tests of the electrical and control systems and loops. The commissioning was finished, when all systems were successfully tested and ready for operation with producer gas. Afterwards the warm commissioning could start.

### 1.2.5 Cold commissioning

Within the cold commissioning phase numerous tests were carried out like (i) final check of mounted equipment, (ii) test for mechanical completion, (iii) test of the electric and control systems and loops, (iv) tests of singular mechanical equipment and machines, (v) tests of functional groups, purging the systems as well as (vi) test of safety equipment and functions.

The main activities in the cold commissioning phase were the filling up of all systems with the foreseen media, bleeding to get rid of residual air and cleaning the process equipment inside by circulation and operation in accordance to the commissioning program.

During the cold commissioning problems occurred like the varying dimensions of column packing that were out of tolerance. Beside this small gas leakages were located at the methanation facility. Furthermore, because of the solidification of the thermal fluid below temperatures of 13°C due to accumulation of gas in the heat transfer system, frequent manual 'defrosting' was necessary; whereas the problem was solved by advancements in the insulation and in reliability of the system. Because of the very low temperatures in the winter 2008 the process media froze. Against this background tarpaulins and additional heating devices were installed (cf. Figure 8) to secure the operation.



Figure 8: The PDU wrapped in a tarpaulin

The loss of process liquids on the top of some columns was solved by installation of demister units as well as through new settings of the maximum levels in the process control system.

### 1.2.6 Main activities in the warm commissioning

The activities of the warm commissioning started after the cold commissioning had been finished successfully. The warm commissioning process was done step by step. Part of the



pre-processing has been taken into operation up to the compression stage as a first step. That means that wood gas from the gasification plant entered the Bio-SNG unit and passed the tar removal and the compression stage. The partially pre-processed gas was directed to the gasification plant.

In a second step of the warm commissioning the PDU was operated including methanation in December of 2008 the first time. This involved also some steps of the purification up to the compression of raw-SNG. The produced raw-SNG was directed to the gasification plant upstream the gas engine.

Encouraged by positive results of the operation in December 2008 and after some problems had to be tackled that are addressed in the following chapter, the commissioning team operated the whole Bio-SNG unit in June 2009 very successfully. Some 250 h of methanation were achieved and Bio-SNG was produced in steady state operation.

Also within the warm commissioning phase problems occurred like the catalyst deactivation by a leaking water valve, which was solved by installation of new ball valves and optimization of the procedures. Additionally problems in measurement of the gas flow occurred, whereas these issues were solved by installation of a new instrument principle.

## 1.2.7 Bio-SNG production

### 1.2.7.1 Quality of the produced Bio-SNG

The Bio-SNG produced meets the requirements of the Austrian regulations of feeding into the natural gas grid G31, G33 as well as the German regulation G260. This was already the case, when the first Bio-SNG was supplied to the fuelling station on the June 10<sup>th</sup> 2009 shortly after start-up.

Table 1: Quality of Bio-SNG

Criteria	Unit	Value
Wobbe-index	[kWh/Nm <sup>3</sup> ]	14,15
Relative density	[-]	0,56
Higher heating value	[kWh/Nm <sup>3</sup> ]	10,7

Although the higher heating value (HHV) of the produced Bio-SNG was within the limits of pipeline-grade SNG, the HHV could be even bigger, if CO<sub>2</sub> from the CO<sub>2</sub> removal step is compressed and utilized to substitute N<sub>2</sub> used in the gasification plant. The N<sub>2</sub> is used in the CHP for filter cleaning and remains in the wood gas and subsequently in the Bio-SNG. This



substitution was not done in this pilot effort because of the involved investments in the existing CHP. Such a substitution could not only enhance the HHV but would be also attractive from the economic point of view in any complete new Bio-SNG production plant.



*Figure 9: The PDU successfully produced Bio-SNG for the filling station*

### **1.2.8 Process and plant performance**

The PDU demonstrated the feasibility of producing Bio-SNG from wood at pipeline-grade quality starting from a wood gas out of a gasification plant of Güssing type. The selected process and the equipment performed after some optimization mainly as predicted. This is a major success.

### 1.3 Specific results from gasification and methanation

The objective of this work was the optimization of the biomass gasification and the extension of the gas cleaning system necessary for the production of Bio-SNG. This requires a hydrogen rich product gas free of nitrogen. Furthermore, gas impurities such as sulphur and chlorine compounds have to be removed down to levels of about 1 ppm. Against this background two main tasks were carried out:

- Optimization of an allothermal steam biomass gasification
- Advanced producer gas cleaning

#### 1.3.1 Objectives in gasification

Steam gasification leads to a producer gas with high content of hydrogen (up to 40 vol.-%) and methane (up to 10 vol.-%), and very low content of nitrogen. Both properties are necessary for an efficient SNG production.

Such a steam gasification process has been demonstrated successfully in a full technical scale (about 8 MW thermal capacity) at the Güssing biomass power station in Austria. A schematic drawing of the steam blown dual fluidized bed gasifier is shown in Figure 10. Within this innovative gasifier the gasification of the solid biofuels is realised within a steam blown stationary fluidized bed reactor. The heat necessary for the gasification is produced in a fast-fluidized bed combustor. The produced heat is transported from the combustor to the gasifier via a solid circulating bed material.

During the operation of the Güssing allothermal steam gasification several questions concerning the behaviour of the steam blown gasifier could not be answered due to lack of knowledge about the gasification process. Therefore, additional research at laboratory scale is needed. The most interesting parameters are:

- Type, shape and particle size of biomass
- Gasification temperature
- Water content of biomass
- Steam to biomass ratio
- Catalytically active bed materials

Systematic experiments were first carried out at an existing 100 kW<sub>th</sub> pilot plant at the Technical University of Vienna. The main findings were verified at the 8 MW<sub>th</sub> demonstration plant during the demonstration phase.

In this chapter of the report, the studies done up to now concerning the influences of particle size, gasification temperature, water content of biomass and catalytically active bed materials are summarized.

### 1.3.2 Dual fluidized bed steam gasification

At the demonstration plant in Güssing a dual fluidized bed reactor is installed to gasify wooden biomass with steam. The basic idea of this concept is to divide the reactor in two zones, a gasification zone fluidized with steam and a combustion zone fluidized with air. A circulation loop of the bed material is created between these two zones to deliver the heat for the gasification process via the circulating bed material. According to Figure 10 the biomass enters a bubbling fluidized bed gasifier where drying, thermal degasification (volatilization), and partially heterogeneous char gasification take place at bed temperatures of about 850 up to 900°C. Residual biomass char leaves the gasifier together with the bed material through an inclined, steam fluidized chute towards the combustion reactor. The combustion reactor serves for heating up the bed material and is designed as highly expanded fluidized bed (riser). Air is used as fluidization agent in the riser. After particle separation from the flue gas in a cyclone, the hot bed material flows back to the gasifier via a loop seal. Both connections, the loop seal and the chute are fluidized with steam, which effectively prevents gas leakage between gasification and combustion zone and also allows high solid throughput.

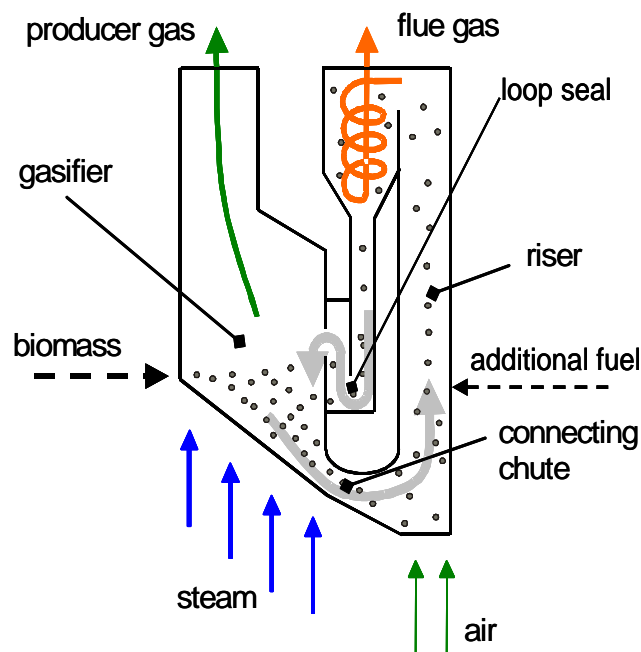


Figure 10: Principle of the dual fluidised bed gasification process



The temperature difference between the combustion and the gasification reactor is determined by the energy needed for gasification as well as the bed material circulation rate. Further parameters with energetic significance are the amount of residual char that leaves the gasifier with the bed material and the gasification temperature. The system is inherently auto-stabilizing since a decrease of the gasification temperature leads to higher amounts of residual char which results in more fuel for the combustion reactor. This, in turn, transports more energy into the gasification zone and thereby stabilizes the temperature. In practical operation, the gasification temperature can be influenced by addition of fuel (e. g. recycled producer gas, saw dust, etc.) into the combustion reactor. The pressure in both gasifier and combustion reactor is close to atmospheric conditions. The process yields two separate gas streams, a high quality producer gas and a conventional flue gas, at high temperatures. The producer gas is generally characterized by a relatively low content of condensable higher hydrocarbons (2 up to 10 g/m<sup>3</sup>N of so called tars, heavier than toluene), low N<sub>2</sub> (< 1 vol %), and a high H<sub>2</sub> content of 35 up to 40 vol % (dry basis). For practical use, Olivine, a natural mineral, has proven to be a suitable bed material with enough resistance to attrition and moderate tar cracking activity.

### 1.3.3 Description of the Pilot Plant

The experiments have been carried out in a so called "Pilot Plant III", which was built in 2003.

To feed the reactor with biomass from a daily hopper two screws are used. They are powered by two electric motors. The former is equipped with a frequency converter; the latter has constant rotational speed and opens out directly into the fluidised bed, to bring the biomass and the bed material in close contact. In order to provide the opportunity of long-term experiments there is also a smaller hopper for bed material to set off the loss of attrited bed material during the experiment. The bed material is fed to the reactor by a screw that is also powered by an electric motor including a frequency converter.

To reach the required combustion temperature additional fuel is necessary. Therefore light fuel oil is inserted into the combustion zone through a nozzle tube. The input of oil is controlled automatically. It depends on the temperature in the gasification zone to control exact the temperature of the gasification zone.

The primary air creates the stationary fluidised bed. It is fed to the combustion zone next to the oil supply to additionally cool the tube and therefore prevent its thermal destruction. The secondary air is provided by an air blower. It is fed to the combustion zone over three nozzles at the expansion part (and creates the transporting fluidised bed). The ancillary air is provided by a separate air blower. It is used to accelerate the heating up period. During gasification it is used for the combustion of the product gas.

Throughout the gasification process the siphons and the gasification zone are fluidised with steam. The feed lines (air, steam) of the siphons and the gasifier are enclosed by heating elements in order to heat the air needed during the heating up period and to overheat the steam required for the gasification process. The steam generator operates with deionised water.

After leaving the gasification zone the formed product gas is lead through a heat exchanger to cool it down to 150 up to 350°C. Because there is no direct use for the product gas provided at the Technical University in Vienna presently the product gas is unified with the flue gas and combustion air and burned in a cyclone that is used as a combustion chamber. The cyclone separates the discharged particles. To assure the completeness of the combustion a pilot burner is installed. The flue gas is then drawn off by the chimney. Figure 11 displays the simplified flow sheet of pilot plant III.

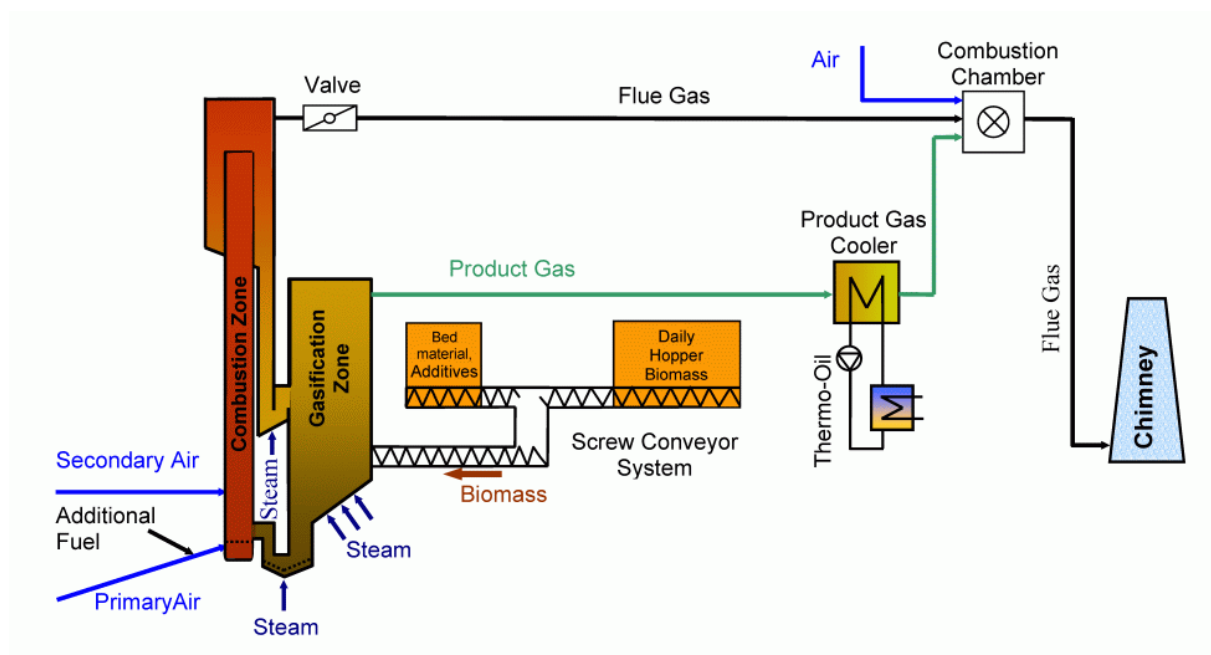


Figure 11: Flow sheet of pilot plant III

### 1.3.4 Experiments for optimisation of gasification

The generated product gas consists of  $H_2$ ,  $CO$ ,  $CH_4$ ,  $CO_2$ ,  $O_2$ ,  $N_2$  and different hydrocarbons such as, for example  $C_2H_4$ ,  $C_2H_6$  and  $C_3H_6$ . As already mentioned, the used analytical device is only able to measure  $H_2$ ,  $CO$ ,  $CH_4$ ,  $CO_2$  and  $O_2$  simultaneously. The amount of steam needed for the gasification consist of steam from the lower and upper siphon and the combustion unit. This summarized amount is simplified as „steam“ in this deliverable.

#### 1.3.4.1 Standardized Gasification Experiment

To be able to benchmark the experiments it is needed to define standardized experiment parameters. The experiments were performed either at 810°C gasification temperature or at 850°C. The mass flow of biomass, calculated on dry biomass, was first kept at 15 kg/h, thereby a combustible heat capacity of 77 kW was reached. The second variation was 22.5 kg/h, which delivered 115 kW.

#### 1.3.4.2 Performed experiments

Several experiments have been performed to generate data on the impact of (i) type of biomass, (ii) moisture, (iii) particle dimension, (iv) gasification temperature and (v) type of bed material on the gas composition, tar content and gasification performance.

No experiments at the gasification temperature of 850°C for biomass with a moisture of 30 % and 40 % has been performed because it was not possible to reach this temperature by the limited size of the combustion zone. The results show that the most of the reactions taking place in the gasifier do not reach equilibrium because the freeboard is not long enough to fulfil the kinetic requirements of these reactions.

#### 1.3.4.3 Results and Discussion

As shown, a series of experiments was accomplished to get repeatable results. Wood chips with a moisture contents from 6 wt % up to 40 wt % were fed into the 100 kW gasifier. Fresh chopped and sieved (screen size 11 up to 20 mm) beech wood chips were used as fuel, which were indoor air-dried till the desired moisture content was reached.

The mass flow of water free fuel, gasification temperature and the amount of fluidization vapour entering the gasification part were kept the same for all experiments carried out. Mass flow of circulating bed material was kept constant as well. Using fuel with higher water content leads to an increased amount of energy necessary for vaporizing the fuel water, and as a consequence thereby the temperature in the gasification part decreases. Thus, holding the gasification temperature constant for all the experiments requires more additional fuel to be co-fired in the combustion part. Due to the high water content a lower gasification temperature (instead of 850°C) is used due to limits of the required additional fuel.

#### 1.3.4.4 Variation water content of biomass

In Table 2 the product gas composition depending on the fuel water content is displayed. With increasing fuel water content the carbon dioxide, methane and hydrogen content of the product gas increases, carbon monoxide content decreases. The fuel power (fp) decreases

with increasing water content at constant mass flow of water free fuel ( $m_{f_{dry}} = 15 \text{ kg/h}$ ). Also displayed is the steam to fuel ratio (sfr) and the mass flow of the wet fuel.

Table 2: *Product gas composition, fuel particle size: 11 – 20 mm, gasification temperature: 810 °C*

particle size [mm]	water content [wt %]	sfr	product gas comp. [vol. %]				[kW]	[kg/h]
			CO	CO <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub>	FP	$m_B$
11 - 20	6	1.0	22.2	25.3	11.6	34.1	76.4	16.0
11 - 20	19	1.2	18.5	28.0	11.1	34.9	74.6	18.5
11 - 20	30	1.4	18.1	28.1	11.0	36.2	72.6	21.4
11 - 20	40	1.6	16.8	26.7	10.6	37.2	70.1	25.0

Increasing the gasification temperature to 850 °C, the results were characterised through higher carbon monoxide and hydrogen contents. Thus, the lower heating value (LHV) increases at 6 wt% fuel water content from 12.5 MJ/Nm<sup>3</sup> to 13.4 MJ/Nm<sup>3</sup> and at 19 wt% fuel water content from 12.2 MJ/Nm<sup>3</sup> to 12.6 MJ/Nm<sup>3</sup> compared to a gasification temperature of 810 °C.

Table 3: *Product gas composition, fuel particle size: 11 – 20 mm, gasification temperature: 850 °C*

particle size [mm]	water content [wt %]	sfr	product gas comp. [vol. %]				[kW]	[kg/h]
			CO	CO <sub>2</sub>	CH <sub>4</sub>	H <sub>2</sub>	FP	$m_B$
11 - 20	6	0.7	24.4	21.7	11.3	35.7	114.6	23.9
11 - 20	19	0.9	20.5	25.8	11.2	36.2	112.0	27.8

The product gas composition of particles < 11 mm is similar as coarser particles 11 up to 20 mm. It must be pointed out that the gasification temperature for particles with water content of 10 wt% was 850 °C and for particles with a water content of 38 wt% was 810 °C.

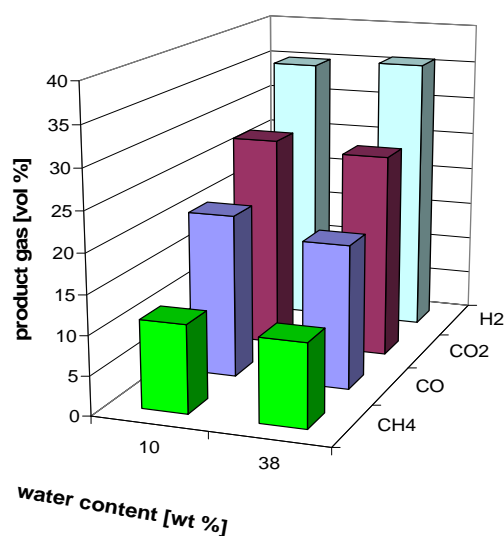


Figure 12: *Product gas composition, fuel particle size < 11 mm*

### 1.3.4.5 Variation of the biomass particle size

The product gas composition depending on particle size is displayed in Figure 13. Obviously, a coarser particle size shifts the carbon monoxide/carbon dioxide ratio to a higher CO content. The amounts of fluidization vapour entering the gasification part were kept constant for the experiments with fuel particle sizes < 11 mm and 11 up to 20mm. Therefore the biomass residence time in the gasifier decreases due to increasing circulation rate. A coarser particle size is supposed to shift the carbon monoxide/carbon dioxide ratio to higher CO content. The hydrogen and methane content changes slightly.

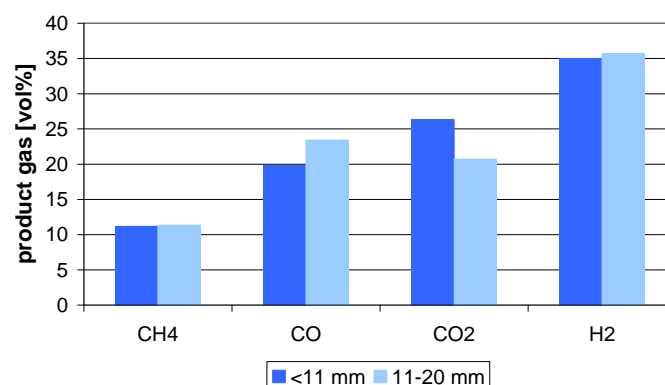


Figure 13 : Comparison product gas composition wood chips with different particle size

### 1.3.4.6 Straw pellets

Due to the low ash melting temperatures of straw (see Table 4) the gasification temperature was reduced to 700 °C to avoid agglomeration in the gasifier. The product gas composition of this experiment is shown in Figure 14.

Table 4: Ash melting behaviour of straw

ash melting behaviour of straw pellets		
beginning of sintering	720	[°C]
beginning of softening	920	[°C]
hemispheric point	1060	[°C]
flowing point	1080	[°C]

There are significant changes compared to wood chips. The methane content is about 15 vol % and the ethene content was measured about four times higher (6.5 vol %). Thus, the lower heating value (LHV) increases significantly up to 14.6 MJ/Nm<sup>3</sup>.



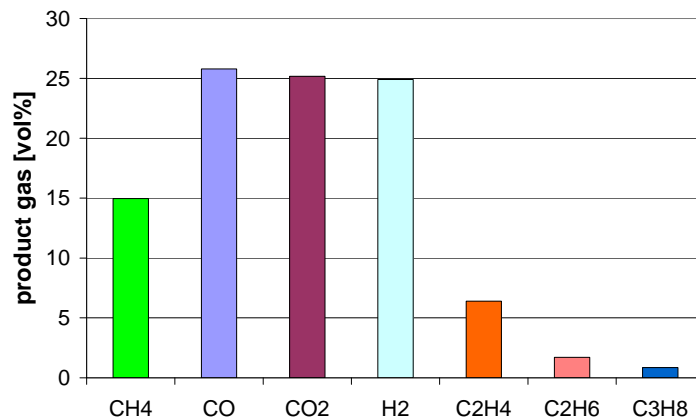


Figure 14: Product gas composition straw pellets

### 1.3.4.7 Tar content and composition of product gas

Beside the composition of the product gas, also the tar content was measured. The influence of fuel water content on the tar content in the product gas is shown in Figure 15. There seems to be a minimum of tar content at a fuel water content of 20 up to 30 wt %. Surprisingly, the tar content of dry (6 wt %) and wet (40 wt %) biomass is nearly the same. No significant changes of tar amount due to an increased gasification temperature of 850°C can be observed.

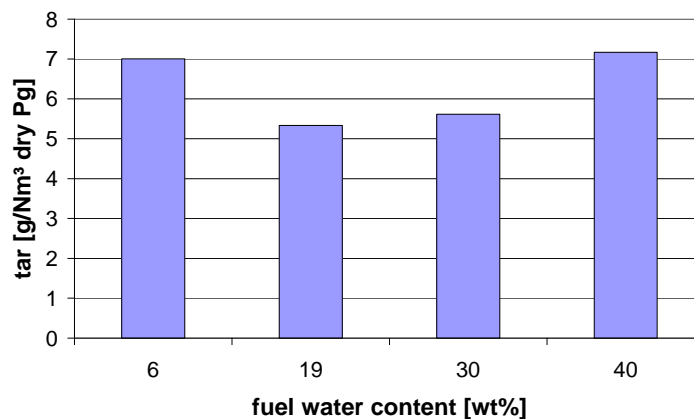


Figure 15: Tar content product gas, gasification temperature: 810 °C

Low gasification temperatures (e.g. 700°C) are causing high tar contents. In Figure 16 the tar content of the product gas from wood chips (WC) and straw pellets (SP) are displayed. The mass flow of dry fuel and the amount of fluidization vapour entering the gasification part were kept constant for these experiments.

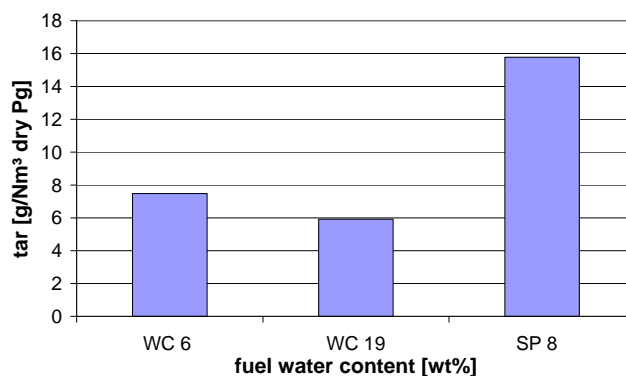


Figure 16 Comparison tar content product gas WC and SP

The GC-MS measurements showed no remarkable influence of the fuel water content on the tar composition. With a gasification temperature of 850 °C, the tar composition shifts to higher polycyclic aromatic hydrocarbon (PAH) content and the concentration of phenol and other oxygen-containing tars decreases.

Table 5: Tar composition

	gasification temperature	
	810°C	850°C
Naphthalene	32.0	35.0
Indene	16.4	10.0
Acenaphthylene	13.5	14.6
Anthracene	7.8	12.1
Styrene	7.8	4.8
2-Methylnaphthalene	4.4	2.4
Phenol	4.9	0.3
Fluorene	3.8	3.7
Pyrene	3.0	5.8
Residue	6.5	9.8

#### 1.3.4.8 Experimental results bed material variation

New bed materials are always investigated in a two step procedure. First, the activity on naphthalene or toluene reforming was investigated in a laboratory scale unit and second the suitable bed materials were tested in the 100 kW pilot plant.

#### Tested materials

The following listed materials have been tested in detail in the laboratory scale unit and selected materials were also tested in the 100 kW pilot plant, like (i) olivine, (ii) ilmenite, (iii)

calcite, (iv) blast furnace slag, (v) silica sand (vi) limestone. The materials have been tested in general pure.

### Laboratory scale experiments

Laboratory tests are very useful to determine the efficient catalytic activity and stability of various catalysts and bed material additives in the particular case under conditions of biomass steam gasification. Synthetic gas mixtures are used with naphthalene and toluene respectively as tar model compounds for this purpose. In the following a screening of several bed materials and additives is presented. On this basis catalytic active materials for pilot scale experiments can be chosen.

### Description of the test rig

The experiments were carried out in a fixed bed quartz reactor with 4 mm inner diameter. The reactor is charged with about 400 mg of catalyst and hold in the temperature zone by quartz wool. The particle size was selected between 250 and 500  $\mu\text{m}$ . The catalyst bed temperature is monitored by a thermocouple placed outside of the reactor near to the catalyst bed. After the reactor a cryo trap is installed to cool down the gas and condense unconsumed toluene as well as water and condensable by-products of the steam-reforming reactions. The condensate is separated from water and analysed by an off-line gas chromatograph. The gases are analysed by an on-line gas chromatograph to get the amounts of  $\text{CH}_4$ ,  $\text{CO}$  and  $\text{CO}_2$ .

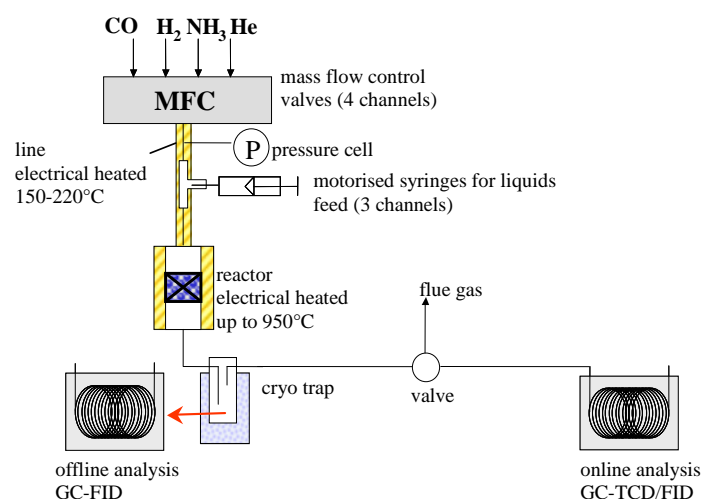


Figure 17: Set-up of the laboratory scale experiments

A series of experiments was accomplished to get repeatable results. The mass flow of water free fuel, gasification temperature and the amount of fluidization vapour entering the gasification part were kept the same for all the experiments carried out. Every material was

tested after the experiment by TGA (thermo gravimetric analysis) to measure the amount of carbon formed on the materials.

### Results of the laboratory scale experiments

Among the tested materials fresh as well as used Olivine from the Guessing gasifier showed reasonable conversion (50 % toluene conversion) and no deactivation over the experimental time of about 6 hours. Ilmenite was less active and deactivated within 1 hour. Calcite and Limestone showed similar conversion rates as Olivine and considering attrition Calcite was chosen as alternative to Olivine to be tested in pilot scale. Blast furnace slag showed conversion rates below 10 %. However, due to the high availability and the cheap price it was also chosen to be tested in pilot scale. As expected Silica sand showed no activity in regard to toluene reforming.

### Results of Olivine in the 100kW pilot plant

A standard experiment means olivine as bed material and a gasification temperature of about 850°C. The fuel used was woodchips with a particle size of 11 up to 20 mm and a water content of 10 wt %. The average producer gas composition of the main components is 38 % H<sub>2</sub>, 25 % CO<sub>2</sub>, 23 % C and 10 % CH<sub>4</sub>, whose trends are displayed in Figure 18. The average gravimetric tar content of the producer gas is 3 g/Nm<sup>3</sup> dry basis.

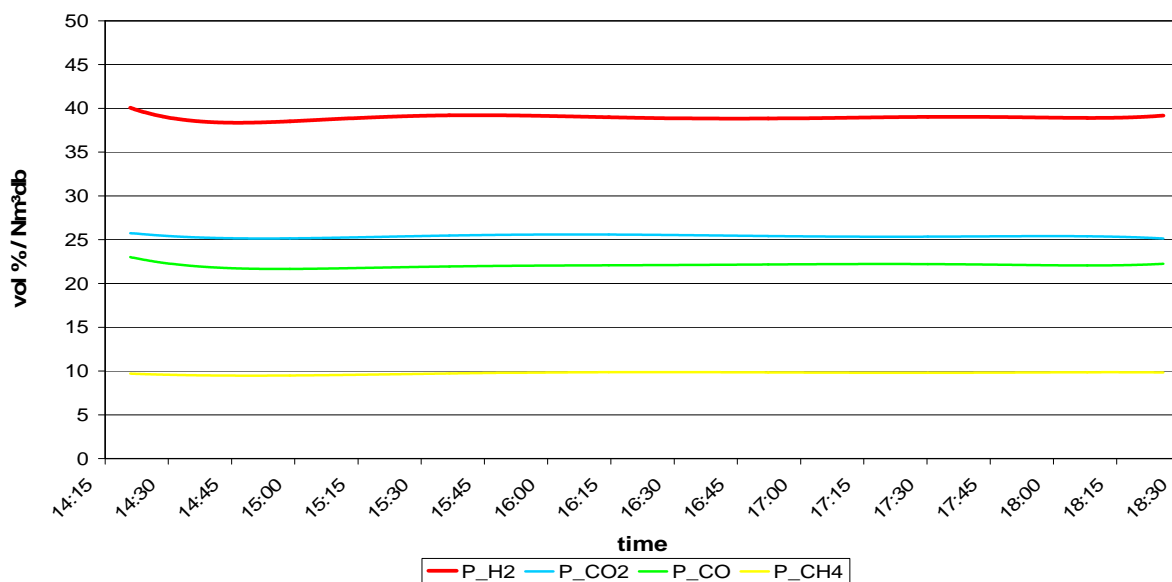


Figure 18: Producer gas composition of the olivine experiment

### Results of blast furnace slag in the 100kW pilot plant

Due to the high availability and the cheap price blast furnace slag was also tested in the pilot plant. After approx. 4 hours of operation the blast furnace slag particles agglomerated in the particle separator (see Figure 19).

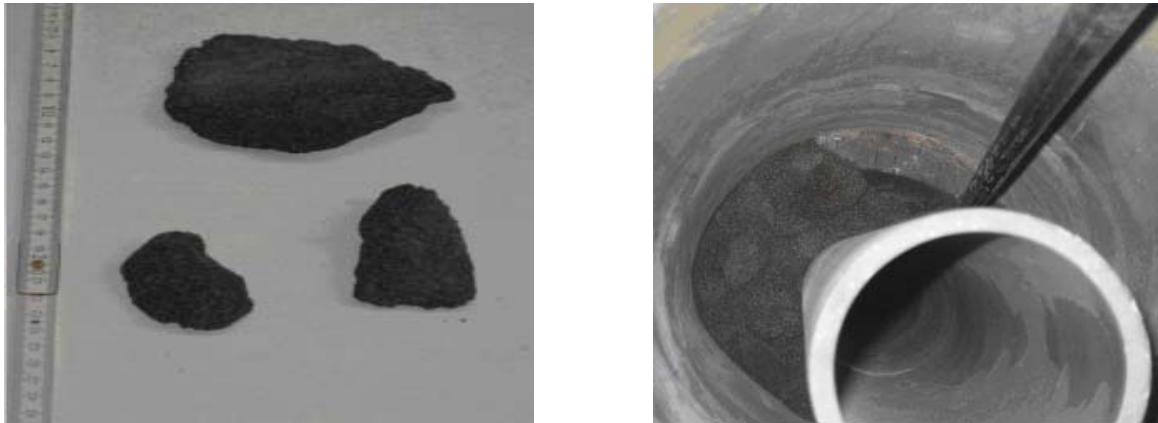


Figure 19: Agglomerated blast furnace slag

Thus the experiment has been stopped due to plugging in the down comer pipe.

### Results of Calcite C14 in the 100kW pilot plant

Calcite C1<sub>4</sub> is a natural mineral which basic chemical composition is CaCO<sub>3</sub> (98.1%) with trace contents of MgCO<sub>3</sub>, SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>. The particle diameter is in an area of 0.5 to 1.3 mm. During steady state operation the gasification of biomass (wood pellets) with this bed material is performed pretty well. The temperatures were held on a constant level of 850°C in the gasification zone and at 900°C in the combustion zone.

The product gas composition remains very constant during the stable phase (see Figure 20). The main average contents are: 47 % H<sub>2</sub>, 22 % CO<sub>2</sub>, 17 % CO and 8 % CH<sub>4</sub>. The rest is N<sub>2</sub> (around 3 %) and carbon fractions higher than methane. In contradiction to the micro reactor experiments the calcite C1<sub>4</sub> shows considerably lower tar content of the producer gas (0.25 g/Nm<sup>3</sup> dry basis) than olivine.

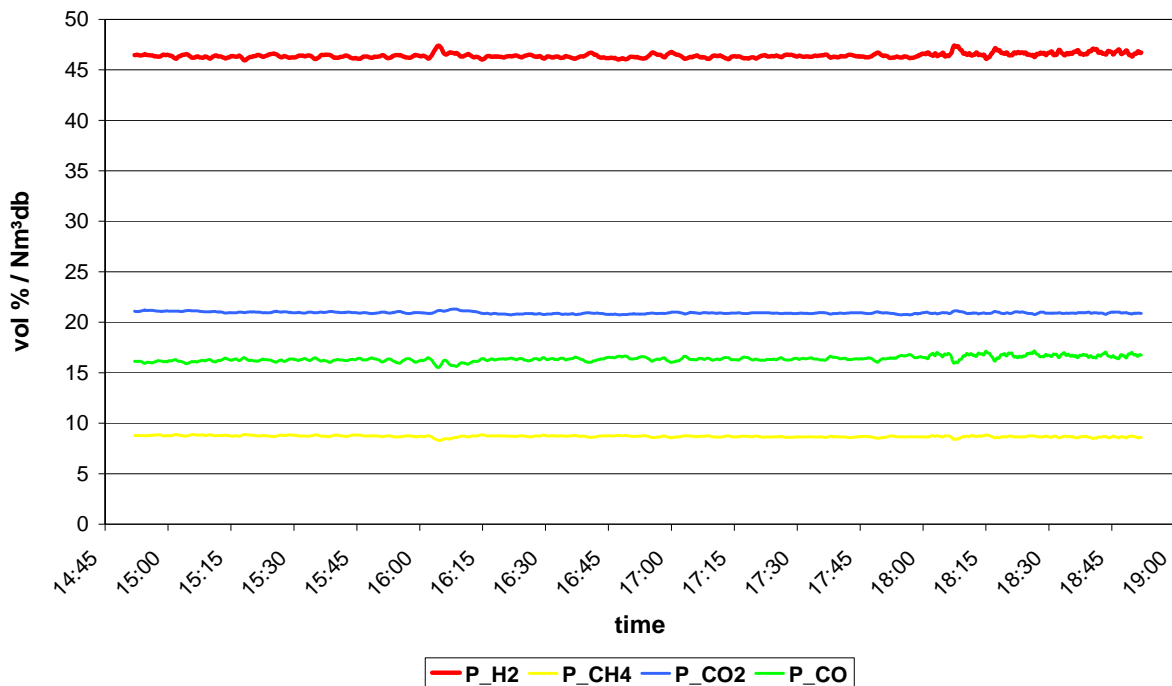


Figure 20: Producer gas composition of the C14 experiment

### 1.3.5 Conclusion of the work performed in gasification

Higher fuel water contents cause increasing hydrogen and methane contents in the product gas. The lower heating value at a gasification temperature of 850 °C is 0.5 MJ/Nm<sup>3</sup> to 1 MJ/Nm<sup>3</sup> higher than at 810 C. A variation of particle size shows shifting of the carbon monoxide/carbon dioxide ratio to a higher carbon monoxide content.

Surprisingly, the lowest tar amount is measured at a fuel water content of 20 up to 30 wt %. This findings correlate with experiences gained in Güssing, where fuel with water content below 20 wt% lead to high tar contents in the product gas and problems with plugging in the product gas heat exchanger. Increasing gasification temperature shifts the tar composition to larger carbon compounds.

The poor ash melting behaviour of straw take steps to avoid agglomeration. One possibility is to decrease the gasification temperature. This affects a higher hydrocarbon content of product gas and increasing LHV. On the other side the tar content also increases. To influence the ash melting behaviour also the influence of additives e.g. limestone, kaolin will be investigated in future outside of this project.

Several possible bed materials/additives (Olivine, Ilmenite, Calcite, Blast furnace slag, Silica sand, Limestone etc.) have been tested in laboratory scale. Among these materials calcites

showed the best conversion rates for hydrocarbons (similar to Olivine). Thus, these materials were tested in the 100kW pilot plant to find the best alternative to Olivine. Calcite proved best in regard to attrition behaviour (similar to Olivine), gas composition (similar to Olivine) and tar levels (significantly lower than for olivine).

### 1.3.6 Objectives in methanation

The objective within the research field methanation was the design of the catalytic methanation process, based on experimental mini-pilot plant results and input requirements for the gas pipeline and the confirmation of long term stability of the catalytic reactor system under real operating conditions. The following four main tasks were carried out:

- basic process design for methanation
- optimizing operating conditions for catalytic methanation
- catalyst sample characterization
- regeneration procedures for deactivated catalysts

### 1.3.7 Catalytic methanation of producer gas

Catalytic methanation is the central process in the conversion of producer gas from the gasification of biomass in the Güssing gasification plant to a methane rich gas that can be upgraded to SNG via conventional gas separation processes. The work performed focussed on critical issues connected with the suitability and stability of the Ni-based catalyst for methanation in a fluidized bed reactor. Both, the catalyst and reactor types had been selected before the start of the project by preliminary studies carried out by partner PSI. There were however, at the beginning of the project, considerable uncertainties with respect to the applicability of the reactor concept and the catalyst formulation in technical scale applications. In order to prove the feasibility of the process and the materials involved, research addressing the following issues was carried out:

- catalyst stability for long-term operation of the methanation reactor
- application oriented characterization of catalyst materials before and after use to assess long-term ageing processes and to correlate operating parameters with the state of the catalyst material
- development of strategies for regenerating de-activated catalysts, preferably in situ

### 1.3.8 Long-term stability of catalyst in fluidized bed reactor

In previous experiments using the 10 kW catalytic fluidized bed reactor facility (COSYMA – cf. Figure 21) for converting producer gas to methane and CO<sub>2</sub> at the site of the Güssing power

plant, the lifetime of the catalyst was limited to accumulated run times of 200 h or less, depending on the gas flow applied to the reactor and the amount of catalyst present. It turned out that deactivation of the catalyst was mainly a consequence of sulphur deposition on the catalyst surface. This happened although a sulphur-absorbing filter (ZnO) had been installed in these experiments. The detailed analysis of the sulphur species in the gas and on the deactivated catalyst revealed that organically bound sulphur, which is not absorbed by ZnO guard beds, was the reason for long-term performance limiting performance of the fluidized catalyst.



Figure 21: PSI's 10 kW scale pilot plant COSYMA.

After a number of unsuccessful attempts to control the concentration of organically bound sulphur, a scrubbing system removing such species efficiently was designed by industrial partner CTU and later on put in place by TUV. Partner PSI measured remaining sulphur load which was fed to the COSYMA. Several long-term experiments using the COSYMA pilot plant were carried out to find the optimum operating conditions for a proper carbon management of the catalytic bed (coking prevention). Based on these results, the design parameters for the scaled-up reactor were fixed in close cooperation with partner CTU. With all measures in place to have a good control of sulphur and carbon species relevant for catalyst deactivation, a long-term experiment was started with the goal to reach 1000 h of stable operation at conditions which could be transferred 1:1 to the technical scale reactor being developed by the industrial partner CTU in cooperation with PSI.

The demonstration of >1000h of stable operation of the methanation catalyst and reactor system converting producer gas from the Güssing gasifier was successfully achieved in summer 2007. A graph showing the concentration of the main gas species after the methanation reactor reveals that the optimization of the operating conditions and the control of contaminants in the producer gas can be implemented successfully. There is a deviation



from the horizontal stable line in the CO concentration at about 770 h. As shown in Figure 22, the increase is connected to a carbon deposition that could be removed by a successful in-situ regeneration procedure. In consequence, the activity of the catalyst went up to the old level and again, low CO-concentrations were measured.

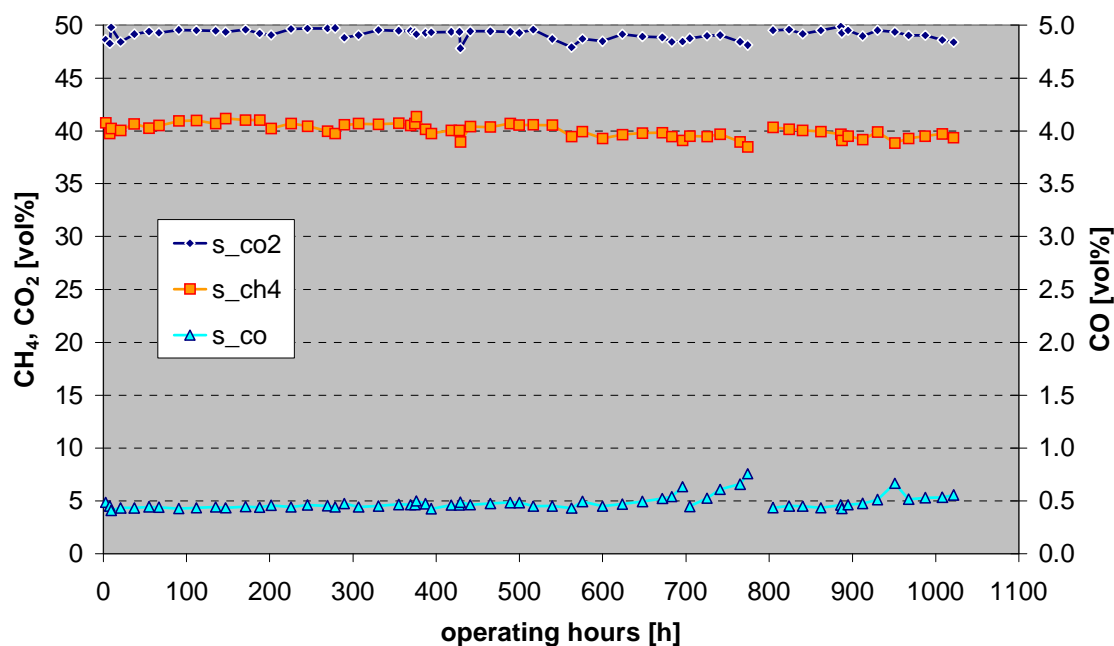


Figure 22: Concentrations of  $\text{CH}_4$ ,  $\text{CO}_2$  and  $\text{CO}$  during the long term experiment using the 10 kW COSYMA pilot plant.

### 1.3.9 Characterization of catalyst Materials

For the industrial development of the technology of catalytic methanation it is important to have available a straightforward method to analyze the catalyst, if possible while the process is still on stream. The 10 kW pilot COSYMA has been equipped with a catalyst sampling system which allows withdrawing samples (typical sample mass of the order of 1 g) from the bubbling fluidized bed while the reactor is on stream. The samples can be retrieved and filled into a sample container under inert or reducing atmosphere, thus preserving the state of the surface at the time of withdrawal.

In order to be able to make a quantitative and straightforward assessment of the state of the catalyst material at the time of sampling an analytical method had to be developed. It turned out that Temperature Programmed Oxidation (TPO) yields the most significant information about the state of the catalyst. In TPO, samples are heated up with a well-defined temperature profile under a flow of an oxygen/argon mixture while a microbalance records the change in mass of the catalyst sample. The gas flow leaving the sample chamber is analyzed by an infrared spectrometer.

Figure 23 shows a typical result of such an analysis. The red curve gives the temperature measured at the sample while the blue curve shows the relative change in weight. It can be observed that after drying of the sample in the first ten minutes, an exothermic reaction takes place at about 250 °C, accompanied by an increase in sample mass. The evolution of the CO<sub>2</sub> (green curve) shows a narrow peak at the same moment. While this CO<sub>2</sub>-peak can be assigned to the combustion of adsorbed tars, the increase in weight can only be explained with the complete oxidation of bulk metallic nickel.

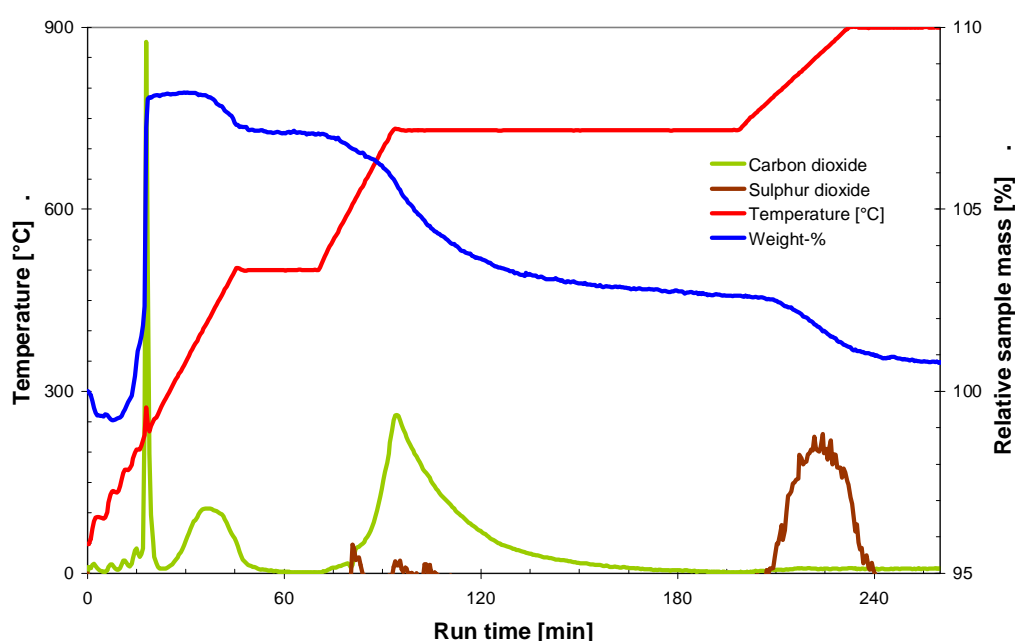


Figure 23: TPO of Ni/ $\gamma$ -Al<sub>2</sub>O<sub>3</sub> catalyst deactivated during methanation experiments with product gas from the industrial biomass gasifier in Güssing/Austria

In the further progress of the analysis, the weight curve only shows losses indicating the combustion of different carbon and sulphur species. At around 480 °C, the combustion of polymeric carbon causes the evolution of CO<sub>2</sub>. At 730°C, graphite is burned that is a constituent of the catalyst. Above 800°C, the weight curve and the SO<sub>2</sub> signal (brown curve) allow the exact quantification of the sulphur content. About 2% weight losses above 800°C in the TPO correspond to the deactivation of the catalyst. However, no further information on the nature of sulphur compounds can be obtained, because all sulphur species on the nickel catalyst are converted to sulphate under TPO conditions.

The method proved to be successful to document the state of the catalyst during the long term experiment documented in Figure 22. TPO traces using the standard heating protocol are shown in Figure 24 and Figure 25. As it can be seen from these figures, the TPO method has been applied to samples taken along the long duration experiment. The CO<sub>2</sub>-evolution

during the TPO allows the conclusion that there is carbon deposition; but the rate of deposition was slow. Nevertheless samples that were taken at 773 h show significant carbon deposition that was removed by an in-situ regeneration procedure.

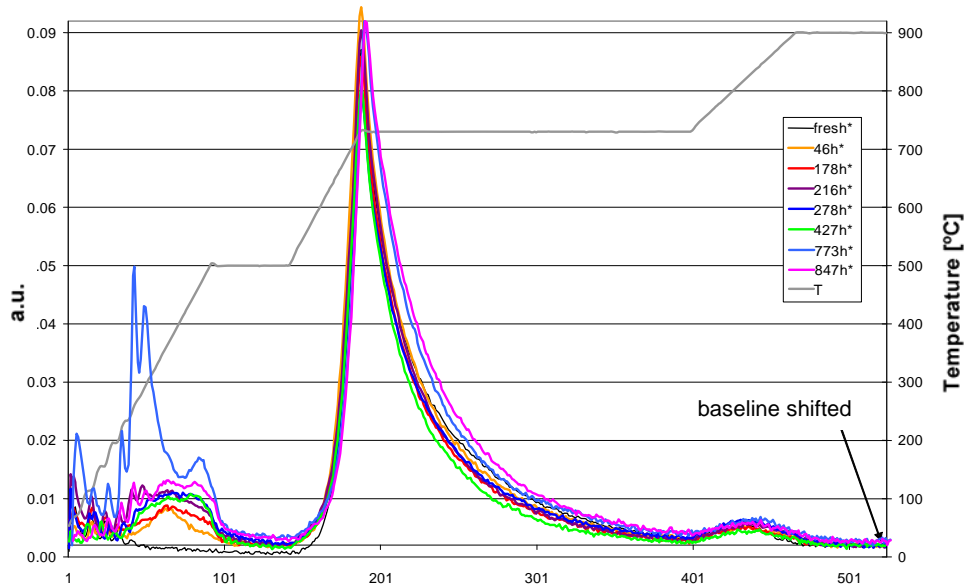


Figure 24: *CO<sub>2</sub>-evolution during TPO of samples from the long duration experiment (the legend gives hours of time-on-stream)*

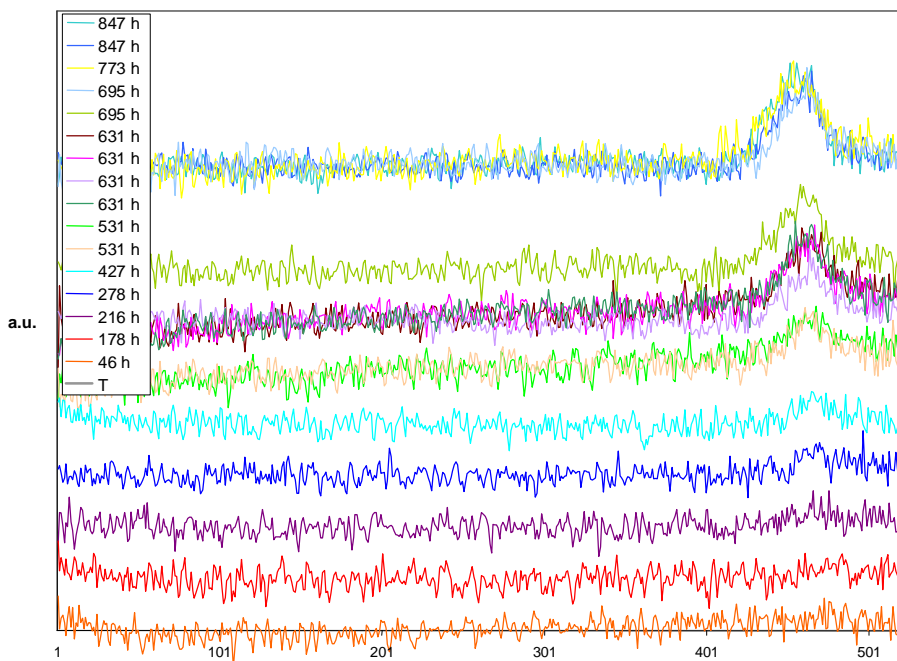


Figure 25: *SO<sub>2</sub>-evolution during TPO of samples from the long duration experiment (baselines shifted; the legend gives hours of time-on-stream)*

In the SO<sub>2</sub>-evolution during the TPO of samples taken along the long duration test, an increasing peak can be observed that corresponds to the sulphur amount deposited on the catalyst. The rate of sulphur poisoning is slow and enables catalyst stability for considerably more than 1000 hours.

### 1.3.10 Catalyst regeneration

Sulphur poisoning is the predominant risk for catalyst failure. When the catalyst reaches a critical load of sulphur its active sites will passivate and the process fails to convert the producer gas to essentially CO<sub>2</sub> and CH<sub>4</sub> with traces of CO. Sulphur poisoning of Ni catalysts is considered to be irreversible. As the TPO analysis shows, sulphur can eventually be desorbed at T = 800°C by oxidation. However, at this temperature the catalyst is deactivated thermally. In contrast to the sulphur poisoning, it has been shown that carbon deposits forming at certain operating conditions can be removed reversibly using steam as a mild oxidant to gasify the surface carbon species.

## 1.4 Use of Bio-SNG in the mobile sector

To demonstrate the overall system “well-to-wheel”, the use of Bio-SNG in methane fuel stations as well as cars was performed.

### 1.4.1 Use in fuelling stations

The objective of this task was to analyse if Bio-SNG can be used in existing fuel stations designed for natural gas.

Therefore a CNG-fuel station was connected to the Bio-SNG demonstration plant. The Bio-SNG was used within this fuel station to fuel cars with Bio-SNG. It was intensively analysed and documented how the system works properly and if any problems occur.

In General, it can be stated, that there is no objection to use a conventional Natural Gas fuel station for processing the gas from a Bio-SNG plant, there are just two outstanding issues, which should be kept in mind during engineering and operation:

- The capacity of the Bio-SNG plant should fit to the fuel station. To anticipate the analysis of the logged data, for this first attempt to feed the Bio-SNG to the fuel station it was not feasible to transmit the maximum volume flow.
- If the Bio-SNG plant is not in continuous operation, the chance that the Bio-SNG will be depleted totally is higher, than for conventional Natural gas fuel stations. This requires a special procedure to ensure the proper filling of the station without any damages to the valves.

### 1.4.2 Use in cars

Besides the testing of fuelling stations additionally driving tests with Bio-SNG fuelled cars were carried out. The objective of this task was the assessment of the effects from Bio-SNG on the emission levels of modern CNG cars. Therefore a car was measured before and after the field trial with the Bio-SNG in the type approval test cycle as well as in real world test cycles. The measurements were performed for two purposes:

- to compare emission levels with standard CNG and with the Bio-SNG
- to compare emission levels before and after the field test with the Bio-SNG

The test fuel respectively the Bio-SNG had the following composition (cf. Figure 26). Out of the measurements it can be stated that the test car had lower exhaust gas emissions with CNG and with Bio-SNG compared to the average of gasoline EURO 4 cars. The emissions measured with Bio-SNG were lower for HC and with  $\text{NO}_x$  than with CNG. For Butadiene lower concentrations were measured in the tests with Bio-SNG than with CNG. For Acetylene CNG resulted in lower exhaust gas concentrations than the Bio-SNG. The other exhaust gas components showed similar levels with both fuels.

<b>MaH Gaslieferung (zu Testzwecken im Zuge der IBN)</b>		
Erwartete Zusammensetzung der ersten Teilbefüllung der Gas-Tankstelle am 11. Juni morgens (260/250/200 bar) gemittelt über rund 130 Datensätze (nicht korrigiert nach Zeit-Interval)		
Analytikdaten noch nicht 'reprozessiert'.		
DU/20090613		
mol%	Stoff	Bemerkungen
0.69	C2H6	
93.96	CH4	reduziert um Korrekturen (s.unten)
0.80	H2	
4.12	N2	
0.09	O2	
0.01	H2O	konservative Schätzung anhand Prozessparameter
0.23	CO2	(lediglich wegen einer kleinen Störung durch Druckpeak relativ hoch)
0.10	CO	'von Hand korrigiert', da teilweise unterhalb Messgrenze (0 rapportiert)
100.00	total	
Ho kWh/nm <sup>3</sup>	relative Dichte zu Luft	
10.61	0.57	
bez. auf Ho		
Werte relevant für H-Gas		
Wobbe s	14.00 kWh/m <sup>3</sup>	

Figure 26: Test fuel composition



## 1.5 Technical, economic and environmental analysis

### 1.5.1 Background

The technical, economic and environmental assessment was carried out to evaluate prospective possibilities of Bio-SNG plants in Europe. In addition it was assessed how the entire Bio-SNG provision chain needs to be designed to compete with other biofuel provision chains of the second generation (e.g. with BtL) regarding technical, economic and environmental aspects.

Against this background six Bio-SNG concepts have been developed for three plant sizes (cf. Figure 27). The concepts can be identified by a synonym consisting of the fuel input power (30 MW<sub>bf</sub>, 100 MW<sub>bf</sub>, 500 MW<sub>bf</sub>) and a number (fluidized-bed methanation – ‘1’ and fixed-bed methanation ‘2’).

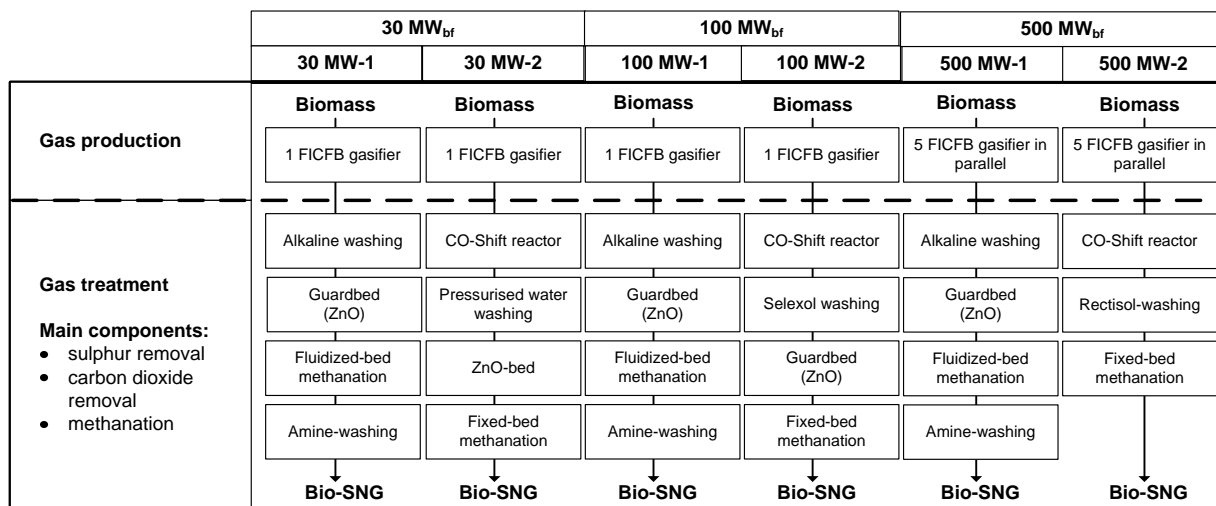


Figure 27: Main components of the six plant concepts to be analysed

Subsequently the technical, economic and environmental aspects of the promising SNG provision chains were assessed.

### 1.5.2 Technical analysis

The technical assessments was carried according to VDI 3780, whereas this included among others (i) analysing a technology and its development possibilities, (ii) assessing the direct and indirect technical impacts of this technology and possible alternatives, (iii) judging these impacts according to defined goals and values, or also demanding further desirable developments, (iv) deriving possibilities for action and design from this and elaborating these, so, that well-founded decisions are possible and can be made.

Furthermore the developed Bio-SNG provision chains have been calculated with regard to their mass- and energy balances based on a simulation-tool developed in MatLab-Simulink®. With help of the calculated mass- and energy flows important values for the technical assessment were derived as e. g. efficiencies, methane yield, heat production for district heating and power production by an ORC process.

In general, four main energetic values have influence on the overall process efficiency: (i) biomass conversion rate (rate of methane output power to biomass input power), (ii) electrical power by-production rate (rate of electrical power production to biomass input power), (iii) electrical power consumption rate (rate of electrical power consumption to biomass input power) and (iv) heat by-production rate (rate of heat produced to biomass input power).

With help of these energetic indicators two overall efficiencies - overall gross efficiency (ratio of the energy content of the products Bio-SNG, gross heat and gross power to the energy content of the all fuels applied (inclusive RME for gas washing)) and overall net efficiency (ration of the energy content of the products Bio-SNG, net heat and net power to the energy content of all fuels applied (inclusive RME for gas washing)) can be calculated. The energetic values and efficiencies of the six process concepts can be seen in Figure 28.

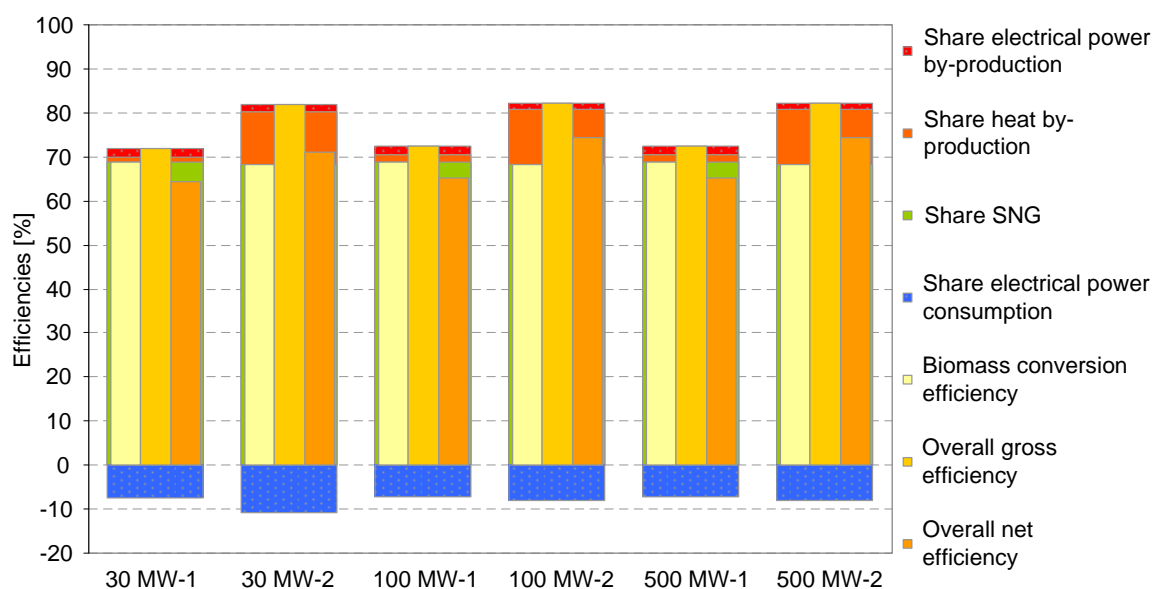


Figure 28: Efficiencies of the analysed plant concepts

The results can be summarised as follows:

- The investigated plant concepts are characterised by almost the same biomass conversion rate (around 68 % of fuel input power). However, they differ by their specific heat by-production rate, their specific electrical power by-production-rate and their specific electrical power consumption rate.
- Due to their similar set up, the plant concepts 30 MW-1, 100 MW-1 and 500 MW-1 have nearly the same efficiency characteristics. Small variation are caused by the different plant sizes and different gas compression rates (in concepts 30 MW-1 the Bio-SNG is compressed to 16 bars before the feed into the natural gas grid; in concept 100 MW-1 and 500 MW-1 the Bio-SNG is compressed to 70 bars before the feed into the natural gas grid).
- As the concepts 30 MW-1, 100 MW-1 and 500 MW-1 use an amine washing downstream the methanation to separate CO<sub>2</sub> from the raw Bio-SNG, they are characterised by higher heat consumption than the other concepts. Therefore, less heat can be “sold” as by-product. This fact leads to lower gross and net efficiencies for concepts 30 MW-1, 100 MW-1 and 500 MW-1.
- The concepts with higher heat by-production have a higher electrical energy consumption than concepts 30 MW-1, 100 MW-1 and 500 MW-1 due the high electrical energy requirement of their sulphur and carbon dioxide removal systems.

### 1.5.3 Economic analysis

#### 1.5.3.1 Bio-SNG provision costs

The Bio-SNG provision costs are variable, depending on the economy of scale of up-scaled plant concepts, biomass provision costs, applicable engineering standards, etc. It is a general observation in plant engineering that the specific production costs are decreasing with increasing plant size. This can also be assumed for the production of Bio-SNG from solid biofuels. In general the effect of the economy of scale causes a nonlinear increasing of equipment and construction costs by increasing the production capacity. Lower specific investment costs by increasing the plant size are the consequences. Other costs like the specific consumption related costs except the biomass provision costs remain almost unaffected.

Positive indirect effects of decreasing specific total investment costs are lower specific maintenance cost and lower specific insurance costs as a percentage of the TIC. Concept 100 MW-2 and 500 MW-2 have a lower specific consumption of electricity than concept 30 MW-2. The reason for that is the Selexol washing unit with lower electricity consumption than a pressurised water washing unit. This causes an additional reduction of the specific Bio-SNG provision costs.



Including the revenues generated by selling heat and electricity, concept 100 MW-2 and 500 MW-2 have lower specific Bio-SNG provision costs than concept 100 MW-1 and 500 MW-1. But, the same problem like the 30 MW-2 concept still remains, a high amount of heat has to be sold to generate revenues.

Additionally, Bio-SNG concepts with a high plant size will be able to produce Bio-SNG on a lower cost level. The higher biomass provision costs for up scaled plants (62.50 €/t<sub>dm</sub> (30 MW); 66.91 €/t<sub>dm</sub> (100 MW); 75.47 €/t<sub>dm</sub> (500 MW)) have an influence on the specific Bio-SNG provision costs, too – but the decrease of the total investment costs is characterised through a higher benefit. Finally, the cost calculation of up scaled plant concepts compiled in Figure 29 add up to the result that the largest plant size leads to the lowest Bio-SNG provision costs (approx. 7.5 €/ct/kWh<sub>LHV</sub>).

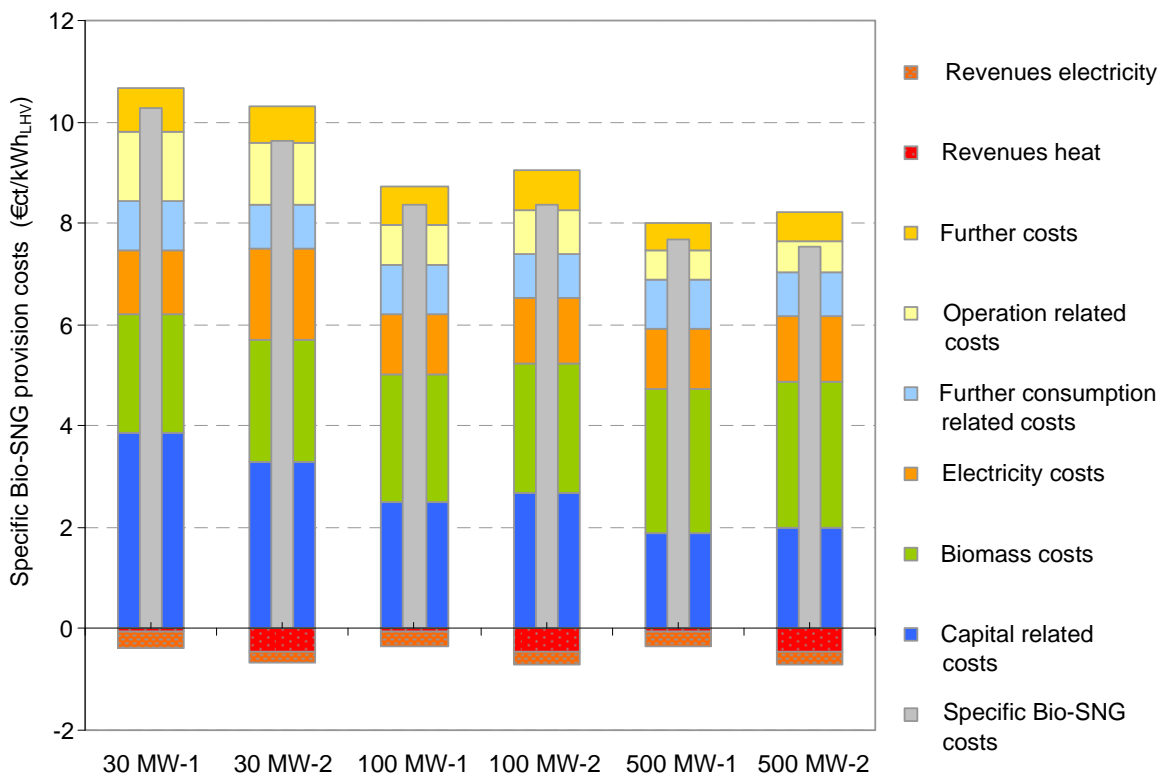


Figure 29: Specific Bio-SNG provision costs

### 1.5.3.2 Bio-SNG distribution costs

The specific Bio-SNG distribution costs for different plant sizes and concepts differ about roughly 12 % (cf. Figure 30). They range from 1.3 €/ct/kWh<sub>LHV</sub> for the concept 30 MW-1 to 1.4 €/ct/kWh<sub>LHV</sub> for the concept 500 MW-2. The small variation of the distribution costs for different concepts of the same power size originates from the differences in the expenditures for heating value adjustment.

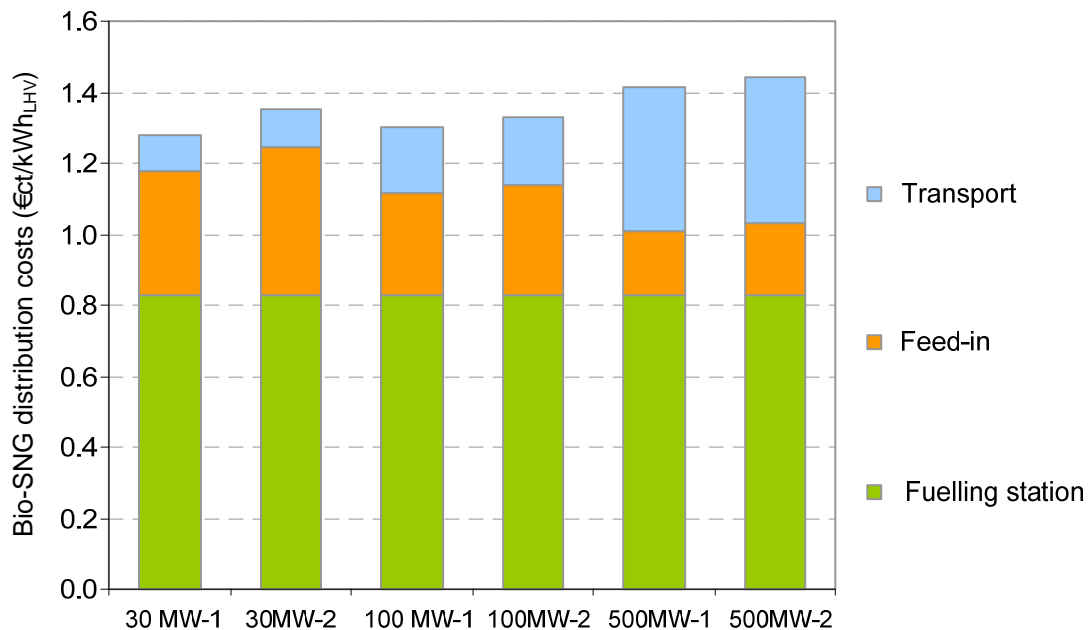


Figure 30: Bio-SNG distribution costs for different plant sizes and concepts

The distribution costs rise with the plant size, due to the higher transportation distance. The increase of the transportation costs is partly balanced by lower feed-in cost. The transportation costs rise with the plant size from 0.1 €/kWh<sub>LHV</sub> (30 MW<sub>bf</sub> plants) to 0.4 €/kWh<sub>LHV</sub> (500 MW<sub>bf</sub> plants) while the feed-in costs decrease from 0.4 €/kWh<sub>LHV</sub> to 0.2 €/kWh<sub>LHV</sub>. The main share of the distribution costs, the costs of fuelling stations, is insensitive to the plant size. The number of fuelling stations that can be supplied rises from 20 (for 30 MW<sub>bf</sub> plants) to 340 (for 500 MW<sub>bf</sub> plants), and hence the costs increase proportionally.

### 1.5.3.3 Well-to-tank Bio-SNG provision costs

The overall specific well-to-tank Bio-SNG provision costs for different plant sizes and concepts differ about roughly 18 % (cf. Figure 31). They range from 11.2 €/kWh<sub>LHV</sub> for the concept 30 MW-2 to 9.0 €/kWh<sub>LHV</sub> for the concept 500 MW-2. The corresponding Bio-cSNG (compressed SNG) cost are 1.51 €/kg and 1.21 €/kg, respectively. This is about 1.2 - 1.5 times more than the present CNG retail prices.

The variation of the overall costs is mainly caused by the plant size (economy of scale). For different concepts of the same power size, it is less than 4 % at 30 MW<sub>bf</sub> and even smaller for bigger plant sizes (see 1.5.3.1).

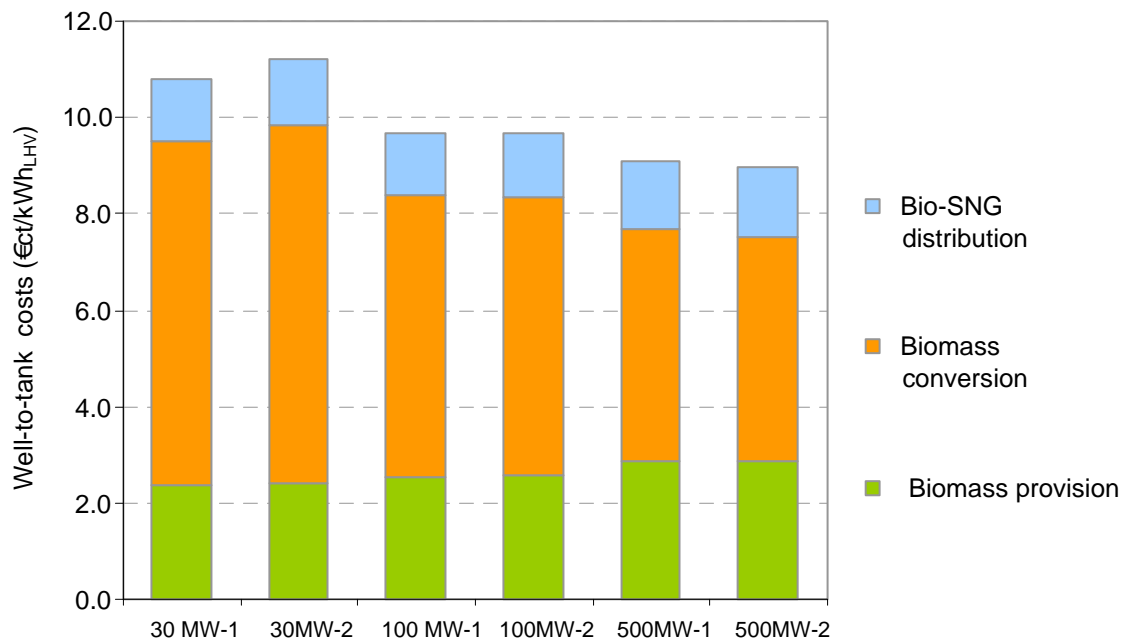


Figure 31: Well-to-tank Bio-SNG provision costs for different plant sizes and concepts

The biomass conversion costs make the largest contribution to the overall costs. They decrease with the plant size, whilst the biomass provision costs and the distribution costs increase. This effect compensates the economy of scale benefits partly and leads to a higher share of the biomass provision and Bio-SNG distribution cost to the overall costs for larger plants, indicating that spatial conditions and the logistic concept will be crucial for the decision on favourable plant capacities.

## 1.5.4 Environmental analysis

### 1.5.4.1 GHG emissions

The calculation of the GHG emissions is carried out in accordance with the methodology of the renewable energy directive (RED). This approach excludes infrastructural expenditures and follows a different methodology for the consideration of produced by-products (GHG emissions are allocated on basis of the lower heating value of the products and by-products).

According to the RED methodology, the 30 MW-1 concept shows the lowest GHG emissions with 27.7 kg CO<sub>2-Eq./GJ</sub><sub>Bio-SNG</sub>. With 39.1 kg CO<sub>2-Eq./GJ</sub><sub>Bio-SNG</sub> the highest GHG emissions are caused by concept 30 MW-2. The results are explained mainly from the high methane emissions during the gas cleaning and Bio-SNG upgrading processes in concept 30 MW-2. The results of the GHG calculation according to the RED approach are shown in Figure 32.

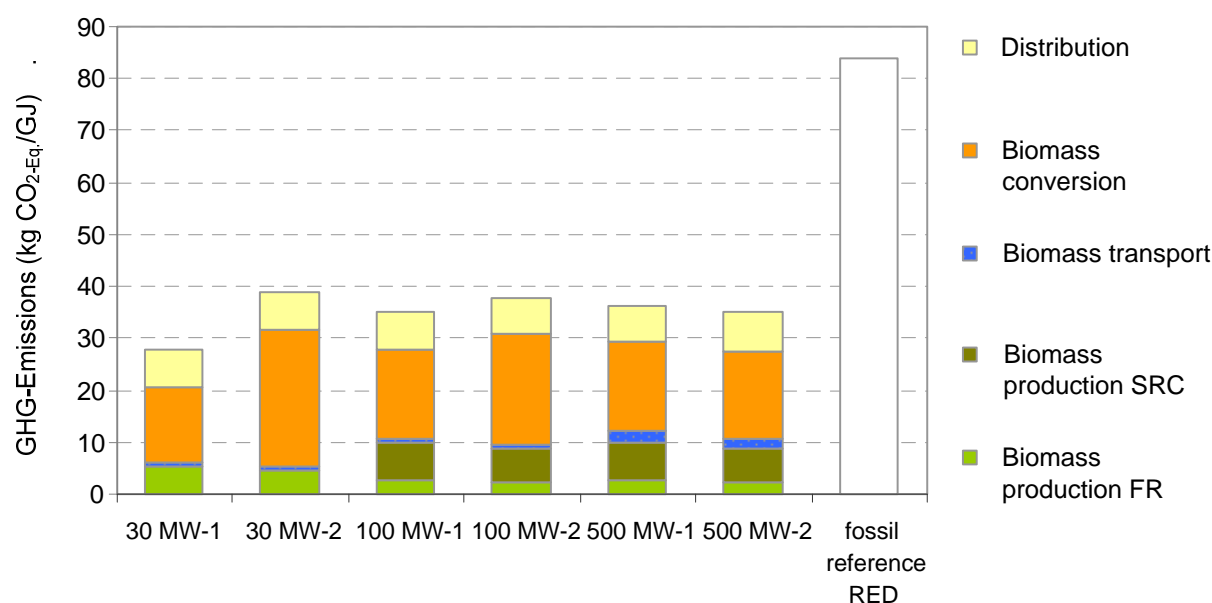


Figure 32: GHG emissions in kg CO<sub>2</sub>-Eq./GJ Bio-SNG, according to the approach of the RED

The current RED proposal raises a minimum GHG mitigation potential of 35 % for biofuels compared to a fossil reference value (83.8 kg CO<sub>2</sub>-Eq./GJ). This minimum greenhouse gas saving will be increased to 50 % in 2017 and to 60 % for new plant installations from 2017 onwards. According to the calculations carried out, all investigated Bio-SNG concepts show significantly better GHG mitigation potentials than the minimum threshold of the RED. Table 6 gives an overview of the GHG mitigation potentials of the investigated concepts.

Table 6: GHG mitigation potential of the investigated Bio-SNG concepts, according to the calculation approach of the RED

Concept	30 MW-1	30 MW-2	100 MW-1	100 MW-2	500 MW-1	500 MW-2
GHG mitigation potential <sup>a</sup>	66.9%	53.3%	58.8%	54.8%	56.6%	58.1%

<sup>a</sup> according to RED methodology, compared to a fossil reference value of 83.8 kg CO<sub>2</sub>-Eq./GJ

### 1.5.4.2 Finite energy consumption

The results of the calculation for the finite energy consumption correlate with the results of the GHG emissions. Due to a comparatively low consumption of electricity during the conversion process and the use of residues as only feedstock source, concept 30 MW-1 shows the lowest finite energy demand (0.54 GJ/GJ<sub>Bio-SNG</sub>) of the considered concepts. Due to an energy intensive conversion process, concept 30 MW-2 has the highest demand (0.70

GJ/GJ<sub>Bio-SNG</sub>) of finite energy resources. The detailed breakdown of the finite energy consumption of different process stages is given in Figure 33.

It is noticeable, that in all investigated concepts the conversion process has the highest impact on the overall results. In the conversion process, the demand for electricity and the used auxiliary materials are the main contributors to the environmental impact.

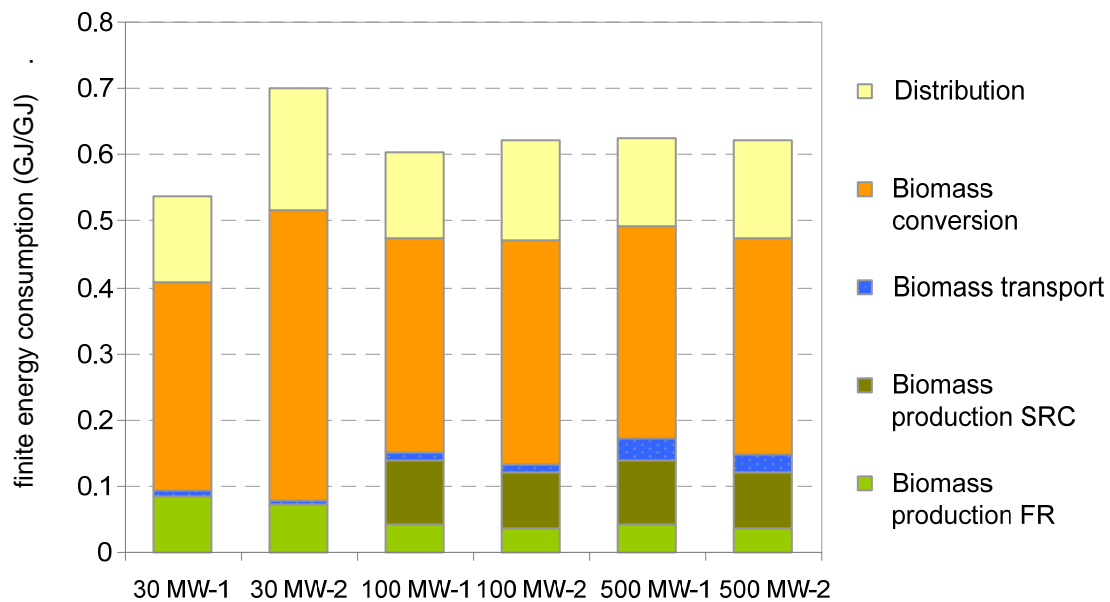


Figure 33: Finite energy consumption of the different concepts in GJ per GJ Bio-SNG, according to the approach of the RED

The results of the calculations show a potential for further improvements of the GHG balance as well as for the consumption of finite energy resources. A reduction of the demand for electricity during the conversion process and/or the choice of a different electricity source (with a higher percentage of renewable energy) seem to be the most promising ways to improve the results of all concepts. Furthermore it was shown that due to the wide range of possible methane emissions, the choice of the gas treatment processes can have a significant influence on the overall environmental performance of the Bio-SNG concept.

## 2 DISSEMINATION AND USE

In the following an overview to the exploitable knowledge out of the Bio-SNG project and its use will be given. Furthermore, the dissemination of knowledge is presented and publishable results shown.

### 2.1 Exploitable knowledge and its use

An overview to exploitable results out of the Bio-SNG project is given in Table 7.

Table 7: Overview table – exploitable results

Exploitable Knowledge	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use	Patents or other IPR protection	Owner & Partner(s) involved
1. New Tar removal stage	Scrubbing system	Biofuels; Energy from biomass	2010	Patent has been applied for in June 2009	CTU, Repotec, further inventors; PSI, TUV
2. Bio-SNG production	Complete process	Biofuels	2010		

The full chain of Bio-SNG production has been demonstrated using the process developed in the course of this work. One patent for a single step of the process has been applied for; while for the remainder of the total system no IP has been protected although there has been a lot of gained IP. The patent has been applied for because this specific process step is applicable for other applications in the field of biomass to energy or fuel as well as for coal to energy or fuel.

Exploitable is the use of the entire process chain for the production of Bio-SNG in industrial scale. The applied for protected process stage might be exploited for other applications. The exploitation of the results shall jointly be made by CTU and Repotec directly, while PSI and TUV will participate in the remuneration gained from exploitation.

The industry partners of the MAH consortium believe that exploitation shall be fairly quickly possible, since CTU and Repotec are already working on several projects, which already have passed the feasibility stage. There is one project in Switzerland, where currently the construction permit is applied for, while for another project in Sweden, already Basic Engineering has been carried out and the construction permit shall be applied for in the course of 2010.

## 2.2 Dissemination of knowledge

Dissemination was a major subject within the Bio-SNG project. On the one hand, participation at several conferences and exhibitions was carried out and on the other hand direct contacts to potential customers took place (cf. Table 8).

The DBFZ mainly presents the overall project on conferences and meetings as well as detailed information that were analysed within the project like biomass resources and logistics for the Bio-SNG conversion plants, biomass gasification technologies and processes as well as methanation technology and processes.

Table 8: Overview table – dissemination activities

Dates	Type	Type of audience	Countries addressed	Partner involved
`06-`08/`09	Project web-site Innovation Award application	General Public General public	Austria, Switzerland	All partners PSI, repotec, TUV, CTU, BKG DBFZ, PSI, EDF,
`06-`09	Publications	General Public	any	repotec, TUV, CTU, BKG DBFZ, EDF, PSI,
`07-`09	Conference	Research	Europe	repotec, TUV, CTU, BKG DBFZ, EDF, PSI,
`07-`09	Exhibition	Industry	World	repotec, TUV, CTU, BKG DBFZ, PSI,
`07-`09	Flyers	General Public	Europe	repotec, TUV, CTU, BKG
`08-`09	Film/video	General Public	France, Germany, Austria, Switzerland	EDF, PSI, repotec, TUV, CTU, BKG

TUV concentrates on the publication regarding the gasifier. The results are published either on conferences, e.g. European Biomass Conference or in journals. Besides this, PSI mainly presented results of the research work containing information to the methanation and gas upgrading.

Major events respectively conferences concerning the topic Bio-SNG were the (i) annual European Biomass conferences, the (ii) conference on thermo-chemical biomass gasification (Leipzig, `07), the (iii) the congress BioSNG'09 (Zurich, `09) the (iv) International conference on Polygeneration (Vienna, `09) as well as the (v) International seminar on biomass gasification and methanation (e. g. Malmö, `07).

The Pilot and Demonstration plant in Güssing also serves as a magnet for dissemination. In the time between erection and commissioning alone, approx. 5,000 people visited the plant. Furthermore, numerous TV teams as well as journals reported about the Bio-SNG project as well as the successful production of biomethane. In the following selected sources are presented:

- The Peninsula Online - Qatar's leading English Daily: "Austrian town becomes an energy model". June 2009
- The Korea times: "Austrian town exports new energy technology". July 2009
- SEV bulletin: "Energie aus Holz – Bäume als Energielieferanten". July 2009.
- Wirtschaftsblatt: "Herausragende Holzforscher und ihr Nobel-Preis". July 2009
- Arte Xenius: "Energie – wie sieht die Versorgung der Zukunft aus?". November 2009

Within the official ceremonies like the laying of the foundation stone as well as the inauguration event of the Bio-SNG plant, several high ranked politicians from countries like Austria and Switzerland were present.

Last but not least the team around the project partner PSI, TUV, repotec, CTU and BKG also won an Austrian and a Swiss innovation award, the so called Schweighofer and Watt d'Or prize.

Within the Bio-SNG project a website was released to provide project relevant information to public as well as advisory board and project partners (cf. Figure 34)

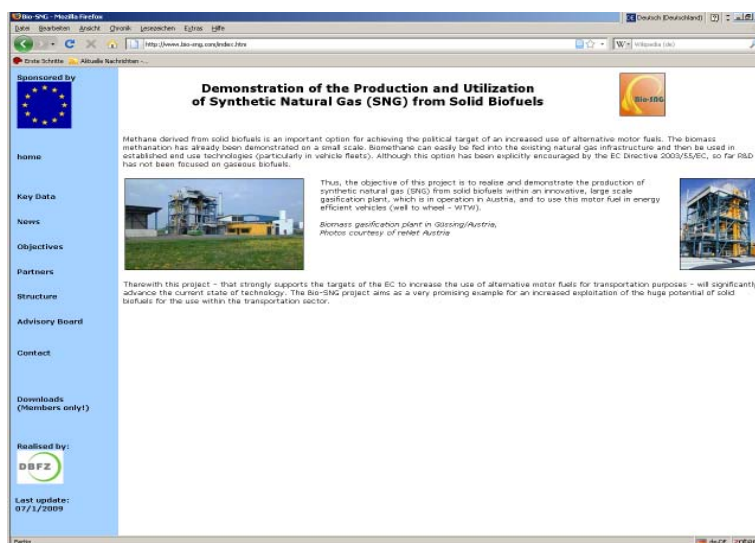


Figure 34: Screenshot of the Bio-SNG homepage



Beside this the project partner EDF realized in 2008 a three minutes animation film, which presents the different energy carriers which can be produced from biomass gasification: (i) electricity, (ii) heat and (iii) Bio-SNG. The movie has been implemented on the home news page of the Bio-SNG website (cf. Figure 35).



Figure 35: Screenshot of the promotion film let

## 2.3 Publishable results

### 2.3.1 Overall process chain

It has been demonstrated, that the entire process chain (wood to Bio-SNG) is feasible and fulfils the expectations in terms of efficiency. Such technology can be applied in the energy industry for the production of sustainable fuel as a replacement of fossil fuel. Interested potential user of such technology is the energy sector, particularly the natural gas industry (distributors). Since the EU decided to replace fossil fuels partially, this technology can fill part of the gap. The technology is not yet fully mature, but a first small industrial scale project will allow to achieve maturity. Such project is in planning. The project had started upon a granted base patent which has been extended. Patent rights have not yet been granted.

### 2.3.2 Pre treatment

In order to run the catalyst of the process, the synthesis gas needs to be purified from sulphur to a very large extent. A process stage has been developed in order to remove sulphur containing tars to an extent not yet known using biogenic solvents which can be regenerated. Such process cannot only be applied for Bio-SNG production but also for other synthesis gases (e.g. from coal) or for other downstream processes (e.g. Fischer Tropsch). Patent protection has been applied for.

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## LIST OF FIGURES AND TABLES

Figure 1:	Consortium of the Bio-SNG project.....	4
Figure 2:	Impressions of the official Bio-SNG plant opening.....	5
Figure 3:	Overall process integration of the new Bio-SNG facility (PDU) into the existing Combined Heat and Power plant (CHP) of the Biomassekraftwerk Güssing GmbH (BKG). ....	7
Figure 4:	Relevant process steps of the Bio-SNG pilot and demonstration unit.....	8
Figure 5:	Calculated noise level 5 m above ground during the night; IP 1 refers to the critical residential building. ....	9
Figure 6:	Site plan displaying the integration of the new methanation PDU adjacent to the existing gasification plant. Furthermore, the situation displays the planned new laboratory building and the Bio-SNG filling station .....	10
Figure 7:	Completion of erection (2008-24-7).....	11
Figure 8:	The PDU wrapped in a tarpaulin .....	12
Figure 9:	The PDU successfully produced Bio-SNG for the filling station .....	14
Figure 10:	Principle of the dual fluidised bed gasification process .....	16
Figure 11:	Flow sheet of pilot plant III.....	18
Figure 12:	Product gas composition, fuel particle size < 11 mm.....	20
Figure 13 :	Comparison product gas composition wood chips with different particle size .....	21
Figure 14:	Product gas composition straw pellets .....	22
Figure 15:	Tar content product gas, gasification temperature: 810 °C.....	22
Figure 16	Comparison tar content product gas WC and SP .....	23
Figure 17:	Set-up of the laboratory scale experiments.....	24
Figure 18:	Producer gas composition of the olivine experiment .....	25
Figure 19:	Agglomerated blast furnace slag.....	26

Figure 20:	Producer gas composition of the C14 experiment.....	27
Figure 21:	PSI's 10 kW scale pilot plant COSYMA.....	29
Figure 22:	Concentrations of CH <sub>4</sub> , CO <sub>2</sub> and CO during the long term experiment using the 10 kW COSYMA pilot plant. ....	30
Figure 23:	TPO of Ni/γ-Al <sub>2</sub> O <sub>3</sub> catalyst deactivated during methanation experiments with product gas from the industrial biomass gasifier in Güssing/Austria	31
Figure 24:	CO <sub>2</sub> -evolution during TPO of samples from the long duration experiment (the legend gives hours of time-on-stream).....	32
Figure 25:	SO <sub>2</sub> -evolution during TPO of samples from the long duration experiment (baselines shifted; the legend gives hours of time-on-stream).....	32
Figure 26:	Test fuel composition .....	34
Figure 27:	Main components of the six plant concepts to be analysed.....	35
Figure 28:	Efficiencies of the analysed plant concepts .....	36
Figure 29:	Specific Bio-SNG provision costs .....	38
Figure 30:	Bio-SNG distribution costs for different plant sizes and concepts.....	39
Figure 31:	Well-to-tank Bio-SNG provision costs for different plant sizes and concepts.....	40
Figure 32:	GHG emissions in kg CO <sub>2</sub> -Eq./GJ Bio-SNG, according to the approach of the RED .....	41
Figure 33:	Finite energy consumption of the different concepts in GJ per GJ Bio-SNG, according to the approach of the RED.....	42
Figure 34:	Screenshot of the Bio-SNG homepage .....	45
Figure 35:	Screenshot of the promotion film let.....	46



Table 1:	Quality of Bio-SNG .....	13
Table 2:	Product gas composition, fuel particle size: 11 – 20 mm, gasification temperature: 810°C.....	20
Table 3:	Product gas composition, fuel particle size: 11 – 20 mm, gasification temperature: 850 °C.....	20
Table 4:	Ash melting behaviour of straw .....	21
Table 5:	Tar composition.....	23
Table 6:	GHG mitigation potential of the investigated Bio-SNG concepts, according to the calculation approach of the RED.....	41
Table 7:	Overview table – exploitable results.....	43
Table 8:	Overview table – dissemination activities.....	44