IEA Bioenergy, Task 33 – Thermal Gasification of Biomass

Workshop

System and Integration Aspects of Biomass-based Gasification

19-20 November 2013, Gothenburg, Sweden

Summary by Dr. Jitka Hrbek, Vienna University of Technology

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Introduction

A joint Workshop between IEA Bioenergy Task 33 (thermal gasification of biomass), and IEA Industrial Energy-related Technologies and Systems Annex XI (industry-based biorefineries) took place in Gothenburg on 19 and 20 November 2013. The topic of the workshop was **"System and Integration Aspects of Biomass-based Gasification".**

Background

There are several national and international initiatives in the area of biomass-based gasification, and such aspects are addressed at different levels, e.g. in both the IEA Bioenergy and the IEA Industrial Energy Related Technologies and Systems (IETS) Implementing Agreements (IA). The main focus of the Bioenergy IA is the technical development status of individual technologies such as gasification, pyrolysis, torrefaction etc. and biorefinery systems, as well as the technical and economic potential of such developments. The IETS IA is more directed towards biomass usage by such technologies within a larger industrial system, i.e. a system integration context, also including the societal level. There is an obvious strong interlink between these two levels, which motivates the exchange of data and results and encourages discussion to understand the underlying methodologies used in both areas to consistently interpret this information between the levels.

Aims

The aims of this workshop were to initiate a dialogue across the technology/system interface, as well as to share methods and results for technical, economic and environmental evaluations of integrated biomass-based gasification systems. Another aim was to identify topics for further international cooperation in these areas.

Presentations overview

The presentations were divided into 4 sessions and copies of all presentation slides can be found at the Task 33 website (www.ieatask33.org). The following table offers an overview of all the presentation given during the workshop.

Table 1: Workshop presentations – overview

Session 1: Biomass Gasification to Fuel Gas; Integration into Power and CHP
H. Wagner, TU of Hamburg-Harburg, Germany **Gasification of Urban Biomass Residues - Possibilities in Hamburg / Germany**
M. Möller, DONG Energy, Denmark **Status of DONG Energy´s Pyroneer Gasification Technology for High Alkaline Fuels**
C.Breitholz, Metso Power, Sweden **Gasification of Biomass and Waste for Production of Power in Lahti and Vaasa**

Session 2: Biomass Gasification into Syngas Part I; Upstream and Internal Integration
H.Thunman, Chalmers University of Technology, Sweden **Beyond 80% Efficiency for Standalone Production of Bio-methane from Wet Biomass**
T.Kolb, KIT, Germany **Biomass gasification for BtL - The Bioliq Process**
I.Landälv, Lulea University of Technology, Sweden **Methanol as Energy Carrier and Bunker Fuel**

Session 3: Biomass Gasification into Syngas Part II; Downstream and Product Integration
R.Rauch, Vienna University of Technology, Austria **Dual Fluidized Bed Gasification for CHP and Production of Advanced Biofuels**
B.van der Drift, ECN, the Netherlands **Chemicals from Gasification**
I. Hannula, VTT, Finland **Production of Synthetic Methanol and Light Olefins from Lignocellulosic Biomass**

Session 4: Methodologies for Assessing Techno-economic Performance and Climate Impact
S. Harvey, Chalmers University of Technology, Sweden **Assessing the Performance of Future Integrated Biorefinery Concepts based on Biomass Gasification**
E.D.Larson, Princeton University, USA **Techno-Economic Systems Analysis of Jet Fuel and Electricity Co-Production from Biomass and Coal with CO2 capture: An Ohio River Valley (USA) Case Study**
M. Talmadge, NREL, USA **Techno-economic and Market Analysis of Pathways from Syngas to Fuels and Chemicals**
A. Faaij, University of Utrecht, the Netherlands **Bio-CCS: Negative Emissions to Meet the Global Carbon Budget**

Session 1: Biomass Gasification to Fuel Gas; Integration into Power and CHP

1.1 Gasification of Urban Biomass Residues - Possibilities in Hamburg / Germany

Hannes Wagner[1], Andrea Stooß[1,2], Stefan Luebben[2], Martin Kaltschmitt[1], Rüdiger Siechau[2], Jan Grundmann[3], Stefan Weber[4]

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In recent years the utilisation of biogenic residues for the generation of energy products has attracted more and more interest on a national, European as well as an international level. Three major reasons are responsible for this development:

- the high potential for greenhouse gas (GHG) reductions due to the use of urban biomass residues
- the avoidance of problems related to the use of agricultural area for energy and thus the food-vs.-fuel discussions and
- the provision of energy from domestic sources and thus the improvement of the security of supply.

Biogenic urban waste with a high content of digestible substances available with high water content is already used in anaerobic digestion plants for the production of biogas. The latter can be further processed in CHP-plants to heat and power and/or can be upgraded to bio methane ready to be fed into the natural gas grid. Compared to this market mature conversion route, the processing of waste streams with a high content of woody biomass through thermochemical gasification is still under development.

Against this background the goal was an assessment of the feasibility of gasification based conversion of biogenic urban waste to combined heat and power (CHP) in terms of technical as well as economic performance for a specific location in Hamburg/Germany.

Thereby the overall process chain including supply and preparation of biomass residues, gasification, gas cleaning and gas utilisation was covered.

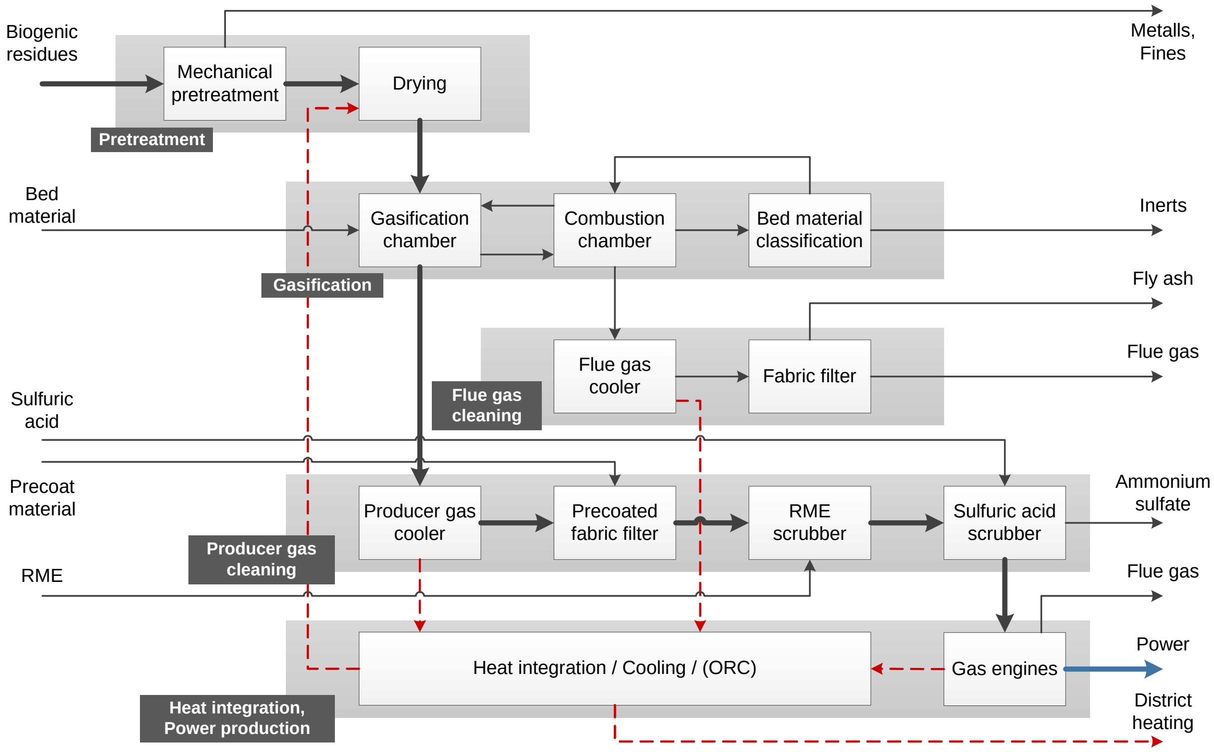

Figure 1: Process overview

The major biogenic waste streams available in Hamburg and possibly suitable for thermochemical conversion were taken into account (e.g. residues from gardens and parks, roadside foliage, urban waste wood). Based on these available residues several gasification concepts with a fuel power input of 7 to 20 MW were investigated, based on existing technologies. In parallel, fuel samples have been gasified within a 100 kW steam blown dual fluidised bed pilot plant at Vienna University of Technology to get first hand data about the gasification behaviour.

Based on these data the performance of the gasifier was modelled with the help of flow sheet simulation software. Beside this, a concept for gas cleaning has been investigated meeting the requirements for utilisation of the provided producer gas in gas engines. Additionally the use of the gas within a CHP unit was simulated and heat integration by pinch analysis was applied. Overall, four various concepts have been developed and assessed.

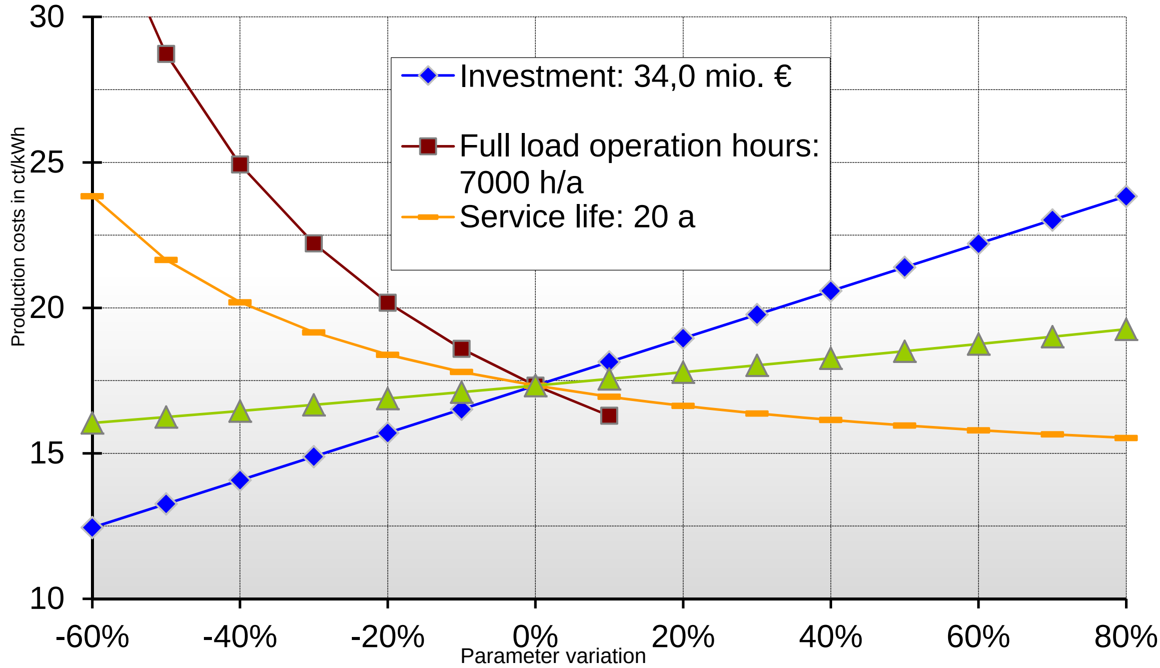

Figure 2: Results: Sensitivity analysis capital costs

This assessment has shown so far the following results:

- In Hamburg there are sufficient woody biomass residues available to operate a gasification plant with a thermal capacity of up to 20 MW. Additionally these residues need to be treated in one way or the other anyway.
- Due to its long history Hamburg has promising locations where such a plant can be erected making use of already existing infrastructural elements allowing for a reduction of the overall costs.
- The simulation results were in a similar range compared to the gasification of conventional wood chips in terms of energy efficiency if excess heat was used for fuel drying.
- The net electric efficiency was calculated to approx. 23.9 % without and 33.2 % with the integration of an Organic Rankine cycle (ORC) for electric power production.
- Including district heating an overall efficiency of up to 65 % can be reached.
- To assure a constant feeding of different fuels the layout of supply, preparation and storage is still challenging since the production of some waste streams like residues from gardens and parks and roadside foliage is fluctuating considerably in the course of the year.

1.2 Status of DONG Energy´s Pyroneer Gasification Technology for High Alkaline Fuels

M. Möller, G. Henderson
DONG Energy, Denmark

After more than 10 years of development, a new technology for gasification of high alkaline fuels such as straw is ready for application in the energy system. In 1993 the Danish government decided that the Energy sector should utilise at least one million tonnes of straw per year in thermal power production. One of the technologies that resulted is the Pyroneer gasifier - a low temperature CFB gasification process owned by DONG Energy.

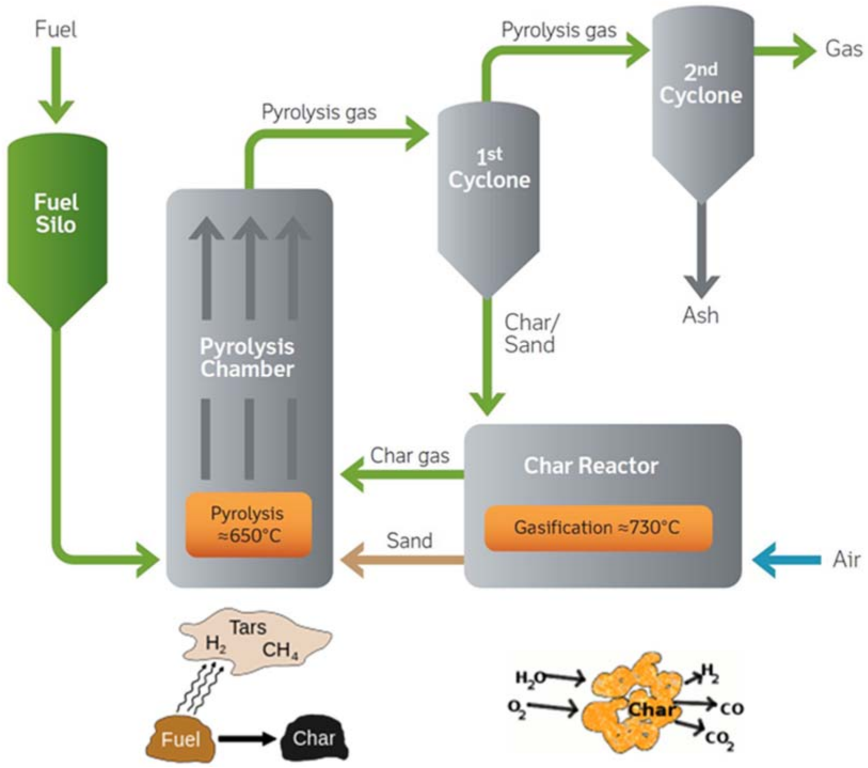

Figure 3: The Pyroneer technology as of today

DONG Energy is one of the leading power generators in northern Europe and has a strategy that 50% of the fossil fuels used in the thermal portfolio of power plants in Denmark shall be replaced by biomass by 2020. As the demand for imported wood pellets increases in line with the multiple biomass conversion projects across Europe, the application of locally sourced high ash and high alkaline biomass has an increasingly strong environmental and economic case for sustainable fossil fuel replacement. Such agri-residues and 'waste' are generally cheaper than wood but are also more challenging due to fouling and corrosion issues caused by their high potassium and phosphorus content.

In 2010, DONG Energy constructed a 6 MW gasifier to verify the Pyroneer technology and demonstrate gasification of these high alkaline feedstocks. The demonstration programme involved assessing if the produced gas could be used to replace fossil fuels in existing boilers, verifying the potential for re-using the ash as fertiliser on farmland and exploring if the technology could be scaled up to a more commercial and economical size.

Figure 4: 6 MW demo plant

Key figures of the demonstration plant

- 1800 operation hours with air blower incl. start-up and cold test
- 1300 tons of straw gasified

Results

- Fuel feed from 5 MW to 7,2 MW
- Stable and safe operation
- Automated start-up after trip to full load in less than 10 min
- Partly automated start-up from cold in less than 24 hours
- Automated and partly unmanned operation

Gas composition

- H_2 : ~ 6%
- CO : ~ 11%
- CO_2 : ~ 13%
- N_2 : ~ 34%
- H_2O : ~ 29%
- CH_4 + : ~ 7%

- Tar compounds are an essential contributor to the LHV of 5.9 MJ/kg
- The ash is low in heavy metals and can be distributed on farmland as a fertiliser

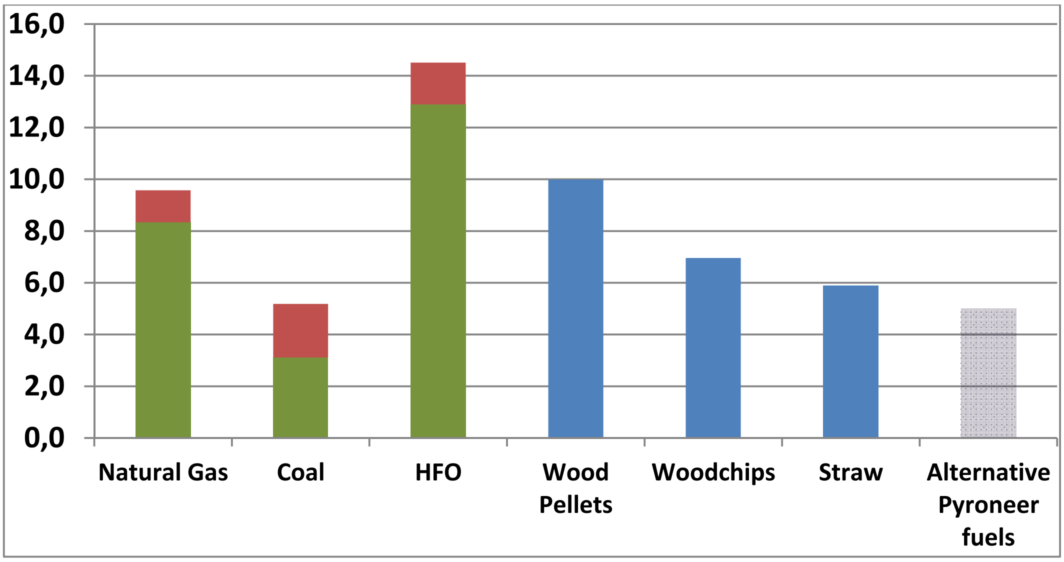

Figure 5: Fuel costs in 2020 (EUR/GJ)

Typical Pyroneer fuels are high alkaline and high ash fuels that are difficult to combust in existing boilers.

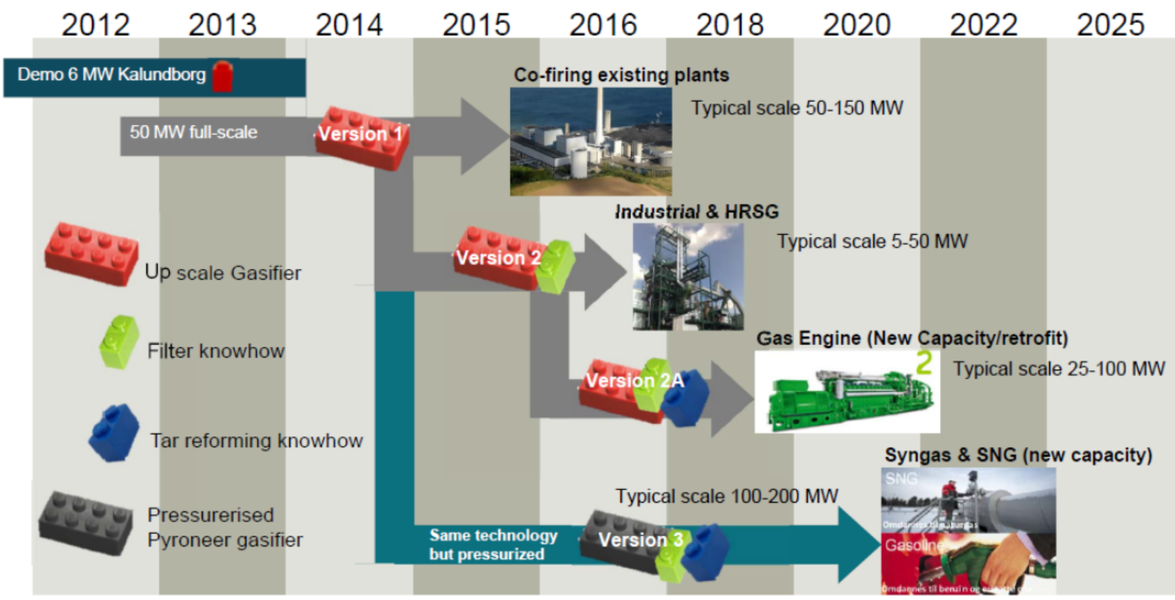

Figure 6: Pyroneer - outlook

1.3 Gasification of Biomass and Waste for Production of Power, the Cases in Lahti and Vaasa

Claes Breitholtz
Metso Power, Sweden

Conversion of solid fuel into gaseous product gas enables replacing conventional fossil fuels with biomass or waste-derived fuels also in applications where solid fuels cannot be used. Gasification also enables new possibilities to increase power production efficiency when utilizing solid fuels. Existing power boilers which do not accept direct feed of solid fuels can utilize gasified fuels. Gasification also enables utilization of difficult fuels in high efficiency power boilers.

Metso has developed gasification technology since the late 1980's and current solutions are based on circulating fluidized bed (CFB) gasifiers.

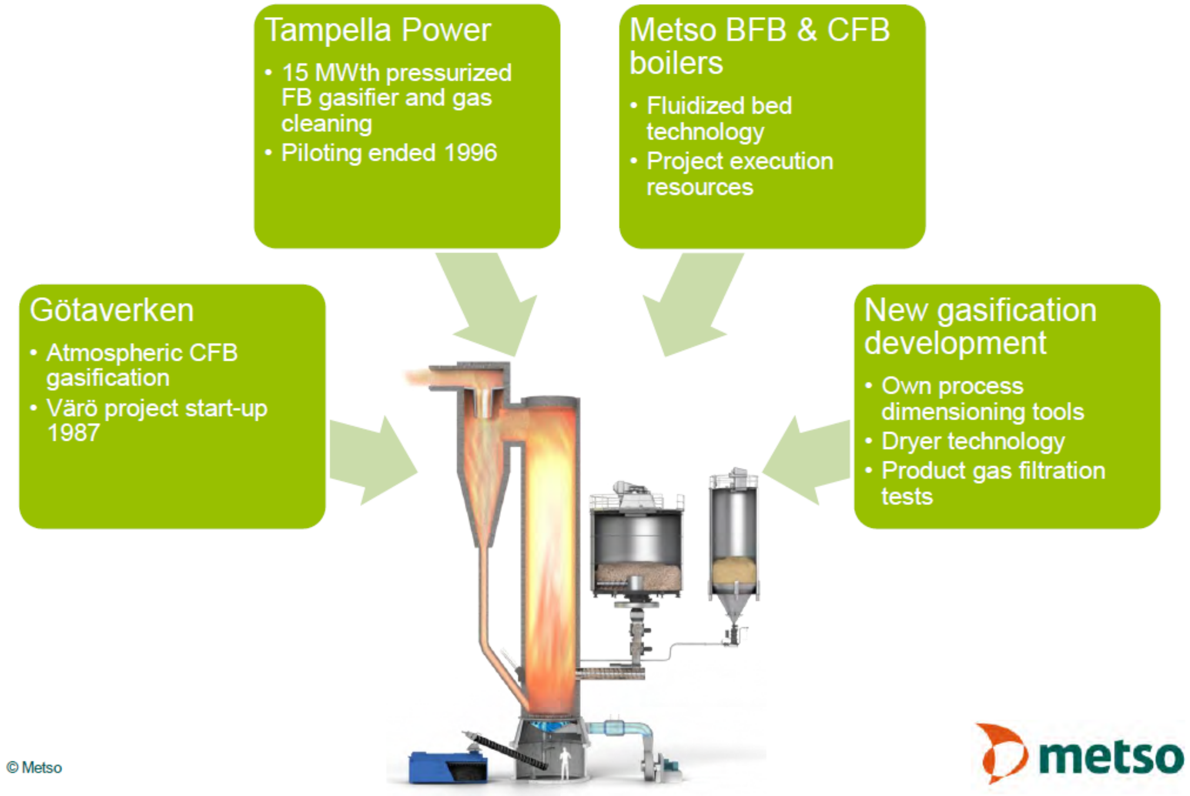

Figure 7: METSO CFB gasifiers – industrial experience

A simple solution "Quick-and-Simple" is a robust solution for clean biomass. A more sophisticated solution "Nice-and-Clean" is suitable for fuels with higher alkali and chlorine contents such as waste-derived fuels or agro fuels.

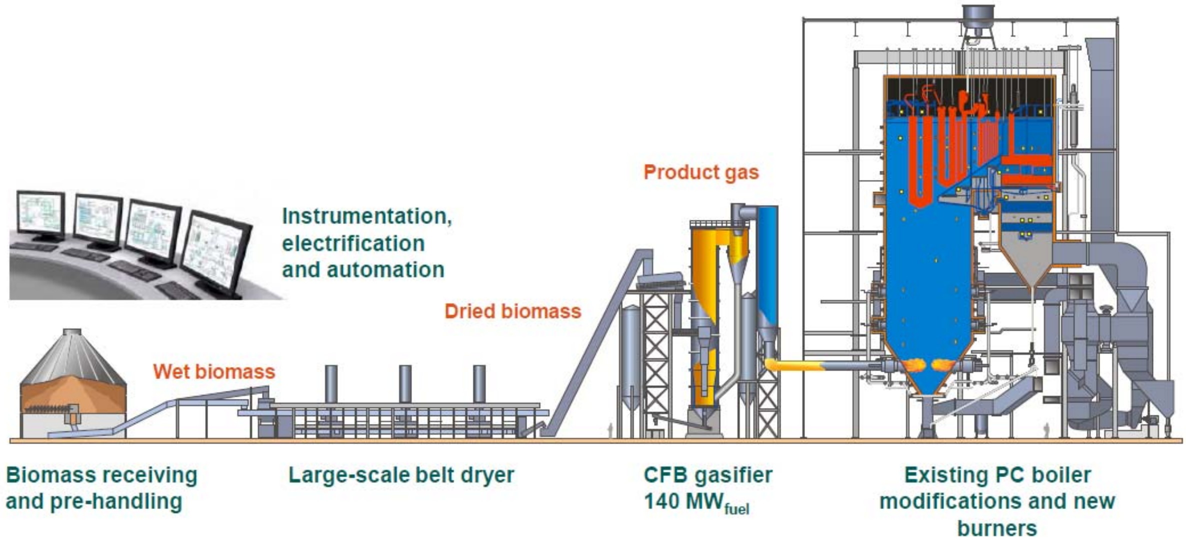

Figure 8: Gasification plant in Vasa

Metso has recently delivered gasifiers in two projects. In Vaasa, Finland, a 140 MW biomass gasifier is producing a gas that is used to replace coal in an existing PC-boiler. This enables to take advantage of the high electrical efficiency of the large scale boiler.

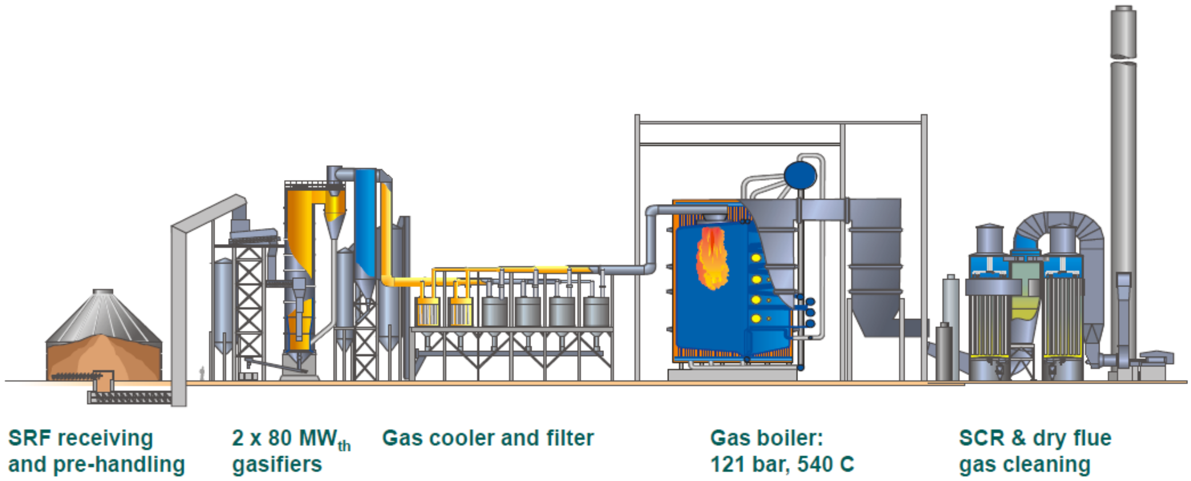

Figure 9: Lahti waste gasification plant

The other project consists of a first-of-its-kind gasification power plant for Lahti Energy that utilizes waste-derived fuels. By hot gas cleaning the corrosive components in the gas are removed. This allows use of the gas in a boiler with conventional steam parameters and construction.

Session 2: Biomass Gasification into Syngas Part I; Upstream and Internal Integration

2.1 Beyond 80 % Efficiency for Standalone Production of Bio-Methane from Wet Biomass

Henrik Thunman, Alberto Alamia, Nicolas Berguerand, Fredrik Lind, Martin Seemann
Chalmers University of Technology, Division of Energy Technology

The possibility and associated challenges to reach above 80 % energy efficiency for the production of bio-methane from biomass was presented.

The current calculations are based on a standalone production plant using an indirect biomass gasifier and are conducted in accordance with the definition used for heat and power plant in Europe. The actual feed biomass is considered to be as received with a moisture content of 50 mass%. The goal of 80 % is 10 to 15 %-units higher than what can be obtained with the process layout of e.g. the GoBiGas project with a planned start of operation late 2013 or beginning of 2014, which is at present is the State of the Art technology.

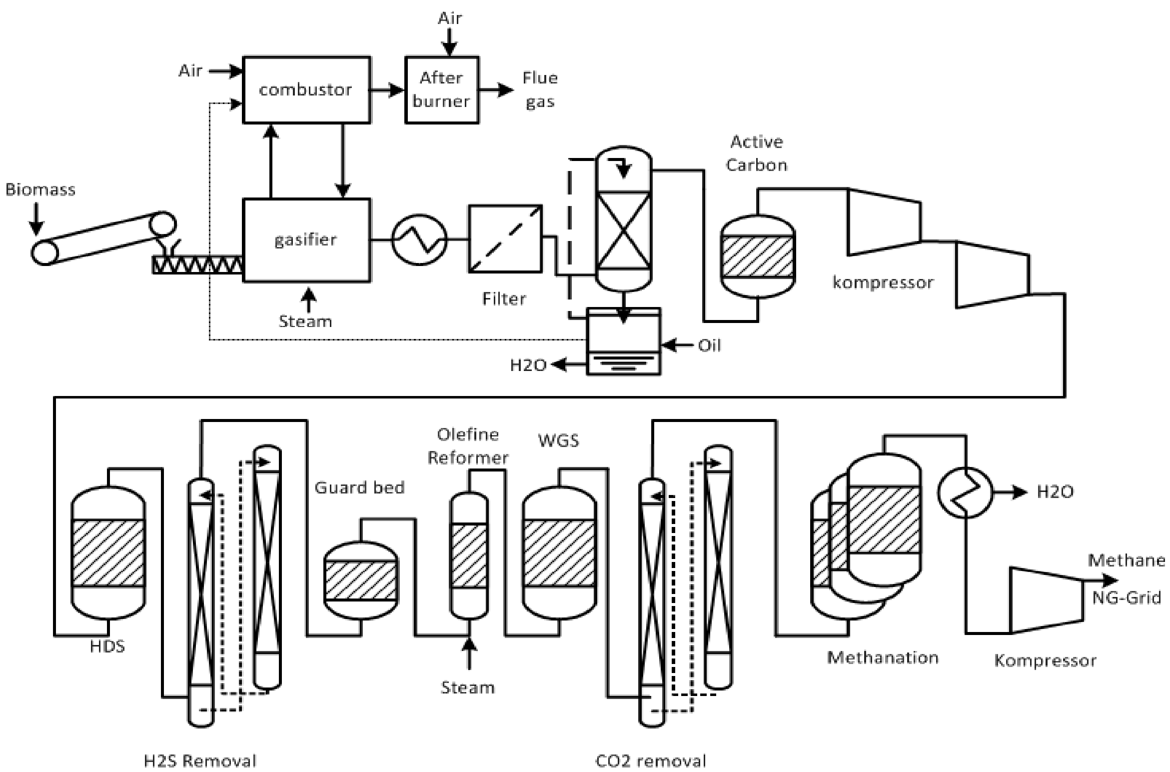

Figure 10: Process Scheme Biomass to Bio-Methane in the GobiGas plant – efficiency around 70%

Considering the whole process, the steps downstream in which the gas is cleaned of impurities are well known and the use of well-established technologies means performance is close to the theoretical maximum even in the first installations. This means that to increase the conversion efficiency from wet biomass to bio-methane, efforts have to be focused on the optimizing of the gasification process and its integration into the overall process. The results from this work show that one can reach very high efficiencies if it is economical and technically feasible to:

1) introduce extensive preheating of air and steam
2) combine drying, preheating and inertization of ingoing fuel
3) limit the steam to fuel ratio in the gasifier
4) minimize hydrogen in gas before compression
5) minimize oxygen transport by bed material used for heat transport and as catalyst for reforming of hydrocarbons in the indirect gasification process
6) reform hydrocarbons to a level that eliminates organic sulphur and oil scrubbing
7) ensure that the char is gasified to the level that is required by the process
8) as a last step to enable the last percentage of efficiency increase, the electrical production from the latent heat produced in the process needs to be maximized, so part of the heat at the highest temperature levels in the process can be provided by electricity

2.2 Biomass Gasification for BtL — The Bioliq® Process

Thomas Kolb
Karlsruhe Institute of Technology

Synthetic fuels from biomass may contribute to the future motor fuel supply to a considerable extent. To overcome the logistical hurdles connected with the industrial use of large quantities of biomass, the de-central / central Bioliq® concept has been developed.

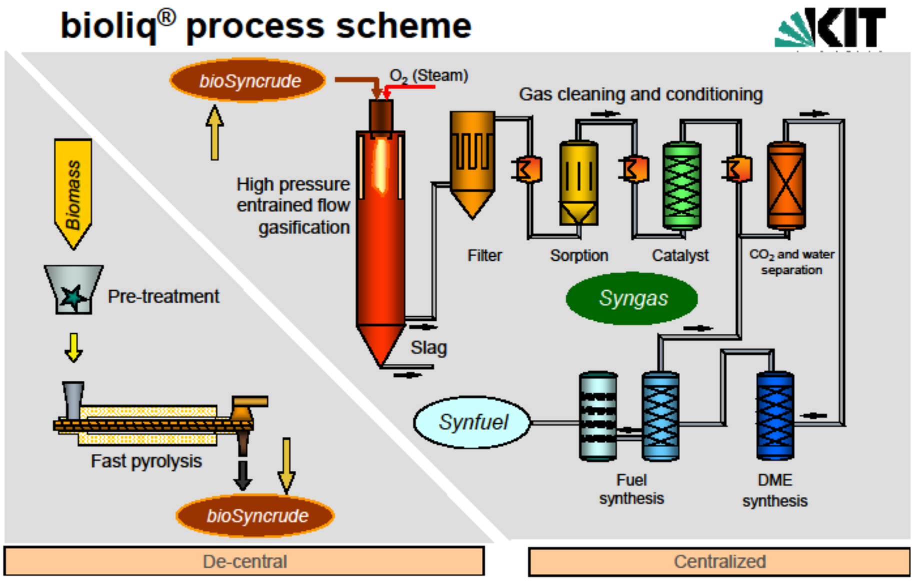

Figure 11: The Bioliq® process scheme

It is based on a regional pre-treatment of biomass for energy densification by fast pyrolysis. The intermediate referred to as biosyncrude enables economic long-range transportation. Collected from a number of those pyrolysis plants, the biosyncrude is converted into synthesis gas, which is cleaned, conditioned and further converted to fuels or chemicals in a central plant of reasonable industrial size.

Gasification is performed in an entrained flow gasifier at pressures adjusted to the subsequent chemical synthesis. For increased fuel flexibility and utilization of ash rich feed materials, the gasifier is equipped with a cooling screen operated in slagging mode. At the Karlsruhe Institute of Technology, KIT, a bioliq® pilot plant has been erected for demonstration of the whole process chain. The 2 MWth fast pyrolysis plant is in operation since 2009; the 5 MWth / 80 bars gasifier, the hot gas cleaning section and the gasoline synthesis via DME were erected in 2011/12. Commissioning of that plant complex was completed in 2013. The gasifier had it´s first operational campaign in July 2013.

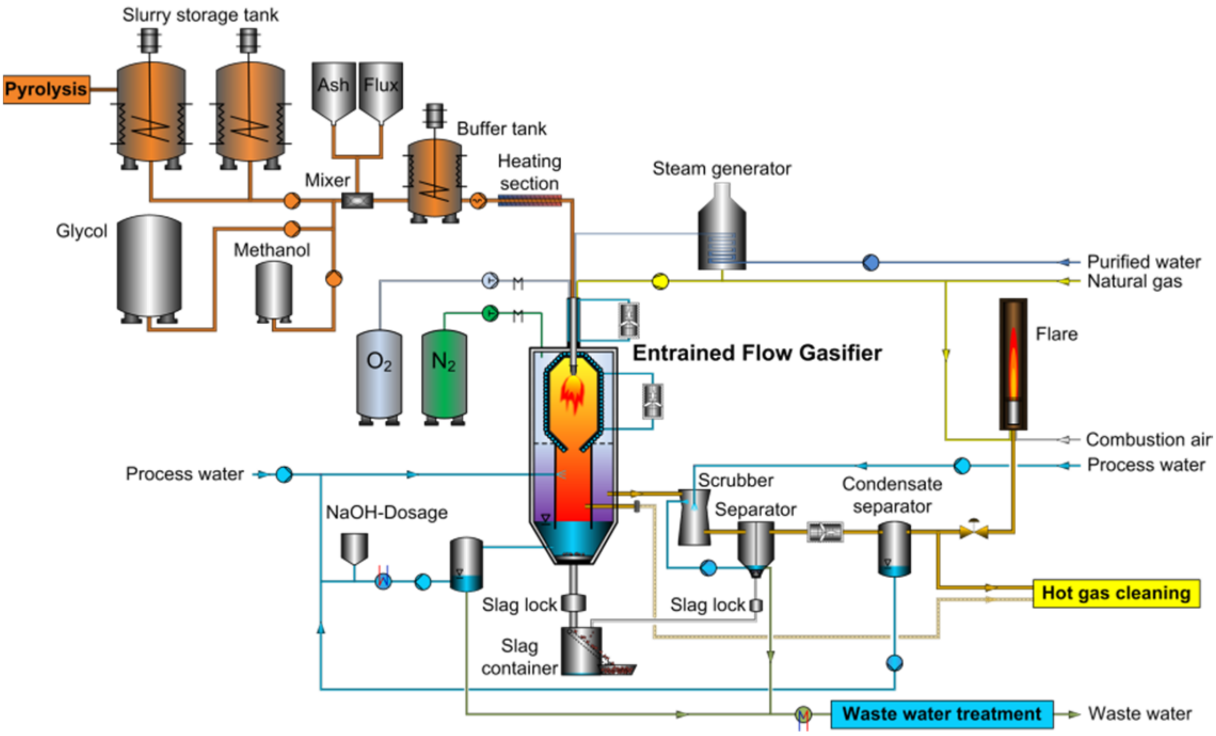

Figure 12: The Bioliq® entrained flow gasifier

2.3 Methanol as Energy Carrier and Bunker Fuel

Ingvar Landälv
Luleå University of Technology, Sweden

The pulp mill site is in many ways the ideal place to develop additional production facilities converting biomass from the forest to new products such as fuels and chemicals. The fact that pulp mills have optimal locations for feedstock sourcing, that their energy system can be optimized, and that pulp mills are looking for complementary businesses are important factors which may lead to such new developments.

Black liquor gasification (BLG) makes use of the unique, renewable energy rich byproduct from the pulping process, black liquor (BL). In some countries in the world this byproduct is large in comparison with the automotive fuel consumption and therefore can play a major role in a transition from fossil to a renewable based energy system.

A way to enlarge the BLG concept is to add other feedstock to the black liquor. BL strongly catalyzes the gasification reactions resulting in complete carbon conversion at 1050 ˚C. This unique property can be utilized in a mixture of BL and pyrolysis oil (PO). Investigations in laboratory scale confirm this assumption and if such a feedstock is simulated for the Chemrec gasification process, about 25% of PO in a BL/PO mixture (weight/dry basis) doubles the syngas production. With this concept Swedish pulp mills would have the potential to produce about half of the current fuel consumption in Sweden in a very energy efficient way.

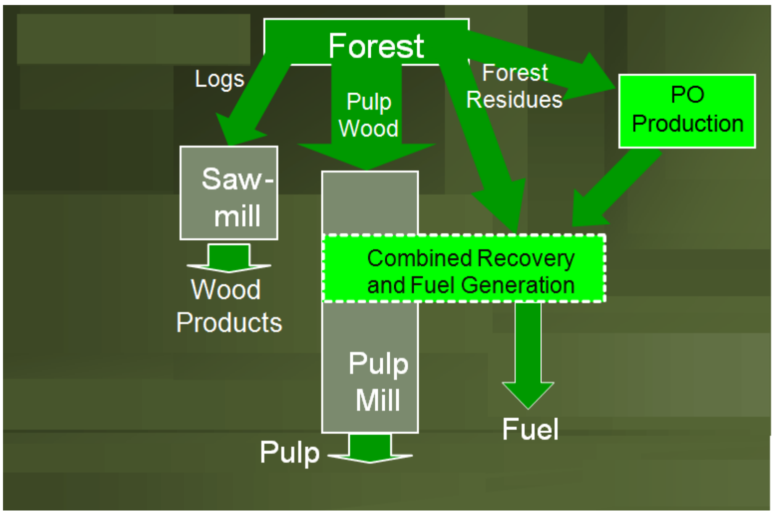

Figure 13: Biomass flow from the forest can be increased adding pyrolysis oil to the black liquor flow

Investigations have mainly been focusing on methanol and DME as fuel products from the mentioned production facilities. A system approach is under development which uses methanol as energy carrier and where the end users are ships (methanol as bunker fuel), HD trucks (DME as a truck fuel) and the chemical industry, and where this new energy system is fed by both fossil and renewable sources.

This system includes methanol storage and handling in harbors. Such harbors, e.g. Gothenburg harbor, can become an optimum location for plants dehydrating methanol to DME which in turn can be distributed to tank stations and become an ultraclean fuel for HD vehicles. In summary: A methanol bunker fuel system in harbors developed by the marine sector will become infrastructure for use of methanol / DME also in other sectors, and open up opportunities for efficient distribution of renewable methanol produced via gasification from biomass materials and wastes.

Session 3: Biomass Gasification into Syngas Part II; Downstream and Product Integration

3.1 Dual Fluidized Bed Gasification for CHP and Production of Advanced Biofuels

Reinhard Rauch
Vienna, University of Technology, Bioenergy2020+, Austria

Indirect gasification is one option to produce synthesis gas already at small scale. The synthesis gas can be used for production of heat and power (CHP), but also for conversion to transportation fuels or chemicals. Also, the production of renewable hydrogen is one economically viable option.

Vienna University of Technology developed such an indirect gasifier and this technology was demonstrated in Güssing.

Actually there are several gasifiers in operation for CHP applications and one in commissioning for production of BioSNG in Austria.

To reach better economic performance, gasification systems are often integrated into larger industrial complex and two examples are given here:

- Production of hydrogen for refineries
- Production of steam for industry by FT synthesis

In the first case, hydrogen for a refinery is produced by biomass gasification. Here the gasification system could be integrated into the refinery, or only the product "BioH2" is delivered over the fence to the refinery. Also, the usage of by-products like SNG is an option and is discussed.

In the second case there is an existing steam demand by industry, and this demand has to be covered by using waste heat from FT synthesis. Thermochemical conversion has the advantage, that heat as by-product can be produced at different temperature levels (850°C after gasifier, 200-300°C from synthesis). So in this study the FT synthesis was scaled in a way that the heat demand of existing industry is covered.

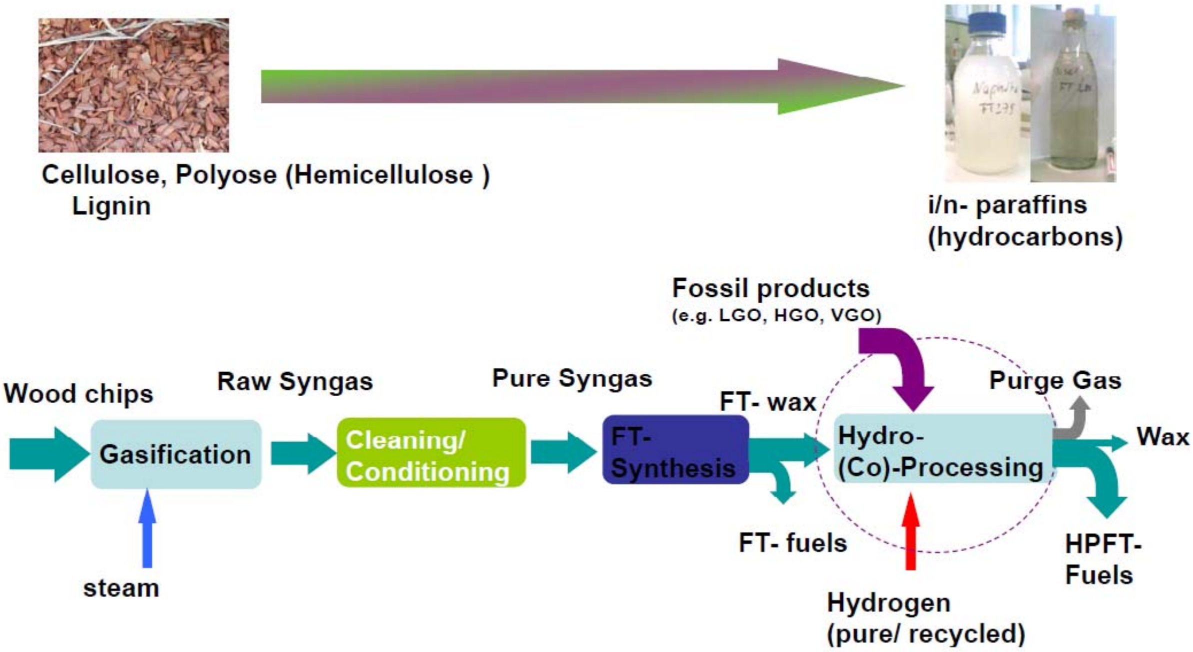

Figure 14: Synthetic biofuels – FT route

Both cases show that the utilisation of the biomass can be over 75% by integration into existing industry, as opposed to stand alone facilities, where only up to 60% utilisation is reached.

3.2 Chemicals from Gasification

Bram van der Drift
ECN, The Netherlands

Biomass and wastes can be used in many different ways to supply renewable products. Power, heat and biofuels are the most well-known products.

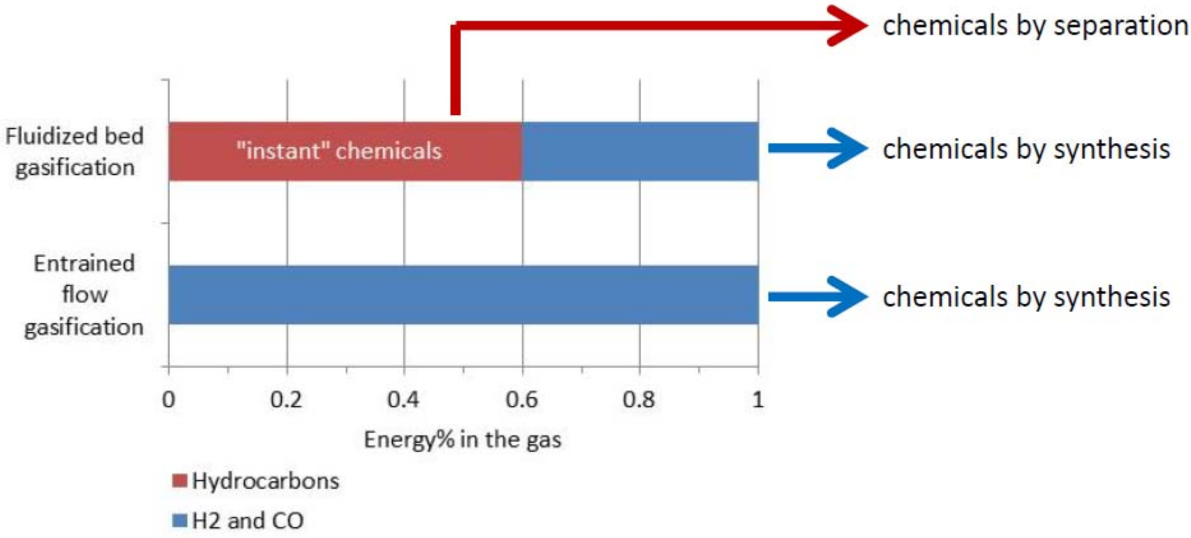

Figure 15: Biomass gasification for production of chemicals

More recently, also Substitute Natural Gas (SNG) attracts much attention. Processes used to produce products like these consist of many different units starting with gasification as the heart of the process, and containing a series of unit operations like separation of tars, sulphur, particles, chlorine, hydrogenation, reforming, CO_2 removal, methanation and drying. The process therefore is relatively expensive and needs to be at large scale to be economically attractive. The process however, offers an additional way of improving the economical attractiveness: co-production of green chemicals.

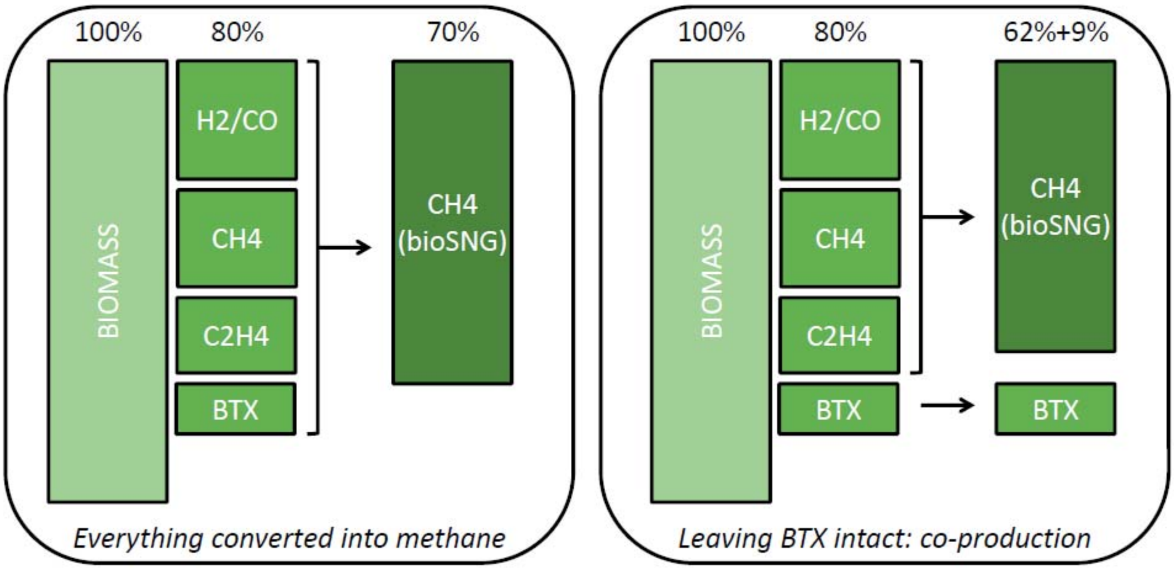

Figure 16: BioSNG processes

Several options exist where green chemicals co-production not only increases the revenues, but also changes the overall process layout in such a way that it becomes cheaper and simpler. The presentation focused on one of these options: co-production of benzene.

It consists of three parts:

- the concept has been modeled to show the pros and cons of benzene co-production
- a benzene separator has been constructed and tested in an integrated test facility
- the gasifier's operating conditions have been changed to optimize benzene yield.

Furthermore, an outlook was given on additional options for the harvesting of valuable chemicals in a biomass gasification process that actually will be a bio-refinery.

3.3 Production of Synthetic Methanol and Light Olefins from Lignocellulosic Biomass

Ilkka Hannula
VTT, Finland

Light olefins are the basic building blocks of petrochemical industry. They are produced by steam cracking of hydrocarbon feedstocks like naphtha or natural gas / shale gas liquids.

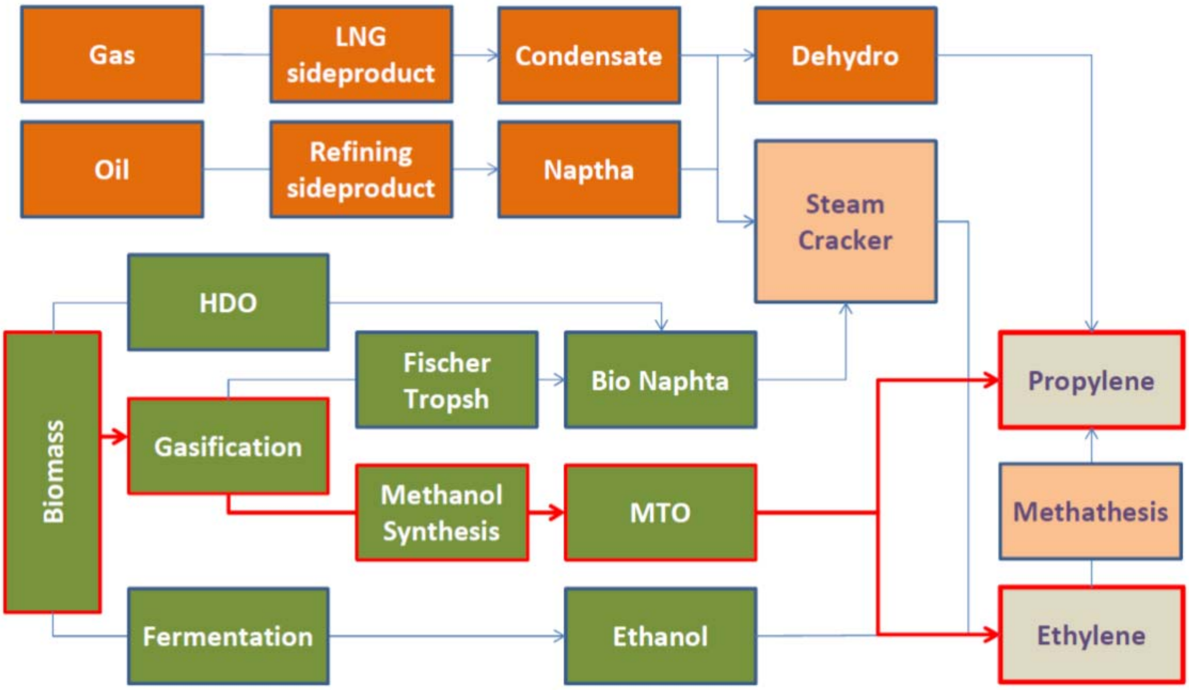

Figure 17: Olefin routes

Rising prices of petroleum feedstocks, together with demand for bio-based feeds on selected markets, have driven technology development to unlock production routes to olefins from alternative feedstocks such as ethanol and methanol. As methanol can be produced from any gasifiable carbonaceous source, including lignocellulosic biomass, the Methanol-to-Olefins route opens up a possibility to produce 100 % bio-based plastics and chemicals.

Large-scale production of synthetic biofuels like methanol requires a fairly complex process that combines elements from power plants, refineries and woodprocessing industry. When such plants are built, it is advisable to integrate them with existing processes to minimise capital footprint and to ensure the efficient utilisation and exchange of heat, steam and byproducts.

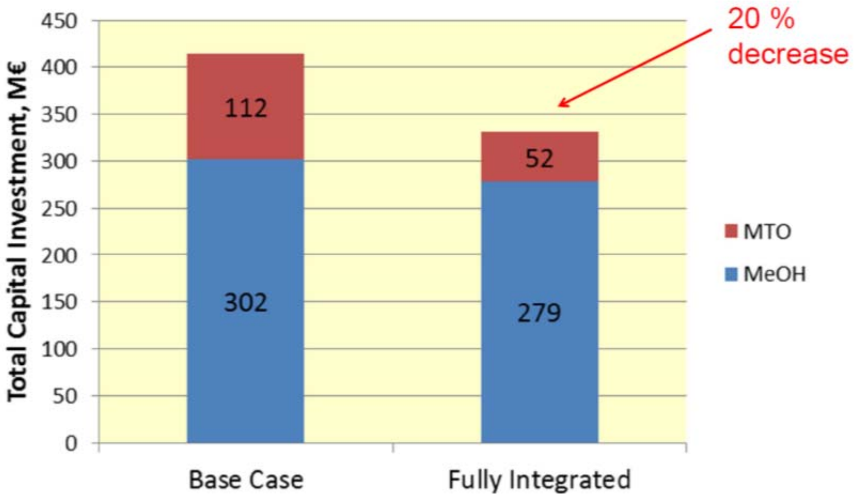

Figure 18: Investment costs estimates for MtO

The presentation gave an overview on the thermodynamic and economic potential of a two-step production of olefins from biomass via methanol. The production of biomethanol takes place in the vicinity of affordable biomass resources in a plant that is energy integrated with a woodprocessing industry or a district heating network. The subsequent conversion of methanol to olefins takes place at a refinery site where separation columns of an existing ethene plant are utilised to partly fractionate the MTO crude.

The study includes conceptual design, process description, mass and energy balances and production cost estimates.

Prices		**Base Case**	**Double Counting**
Electricity	€/MWh	50	50
Tailgas (H2)	€/tonne	1200	1200
Ethane	€/tonne	332	332
Propane	€/tonne	332	332
LPG	€/tonne	332	332
C4+	€/tonne	600	1120
Ethene	€/tonne	829	829
Propene	€/tonne	995	995
Gasoline	€/tonne	750	1400
Distillate	€/tonne	700	1300

Table 2: Assumed product prices

Particular emphasis is given to the effects of energy integration and equipment sharing separately for both conversion steps. The process simulation work is done using Aspen Plus® chemical process modelling software. The analysis builds on the author's prior work with simulation of pressurised oxygen-gasification of biomass and detailed evaluation of large-scale biomass-to-liquids processes.

Session 4: Methodologies for Assessing Techno-economic Performance and Climate Impact

4.1 Assessing the Performance of Future Integrated Biorefinery Concepts based on Biomass Gasification. Methodology, Tools and Illustrating Examples

Simon Harvey and Thore Berntsson

Heat and Power Technology Group, Dept of Energy and Environment, Chalmers University of Technology, Göteborg, Sweden

This presentation proposed to explore methodology for assessing the economic performance and carbon footprint of future integrated biorefinery concepts based on forest biomass gasification technology.

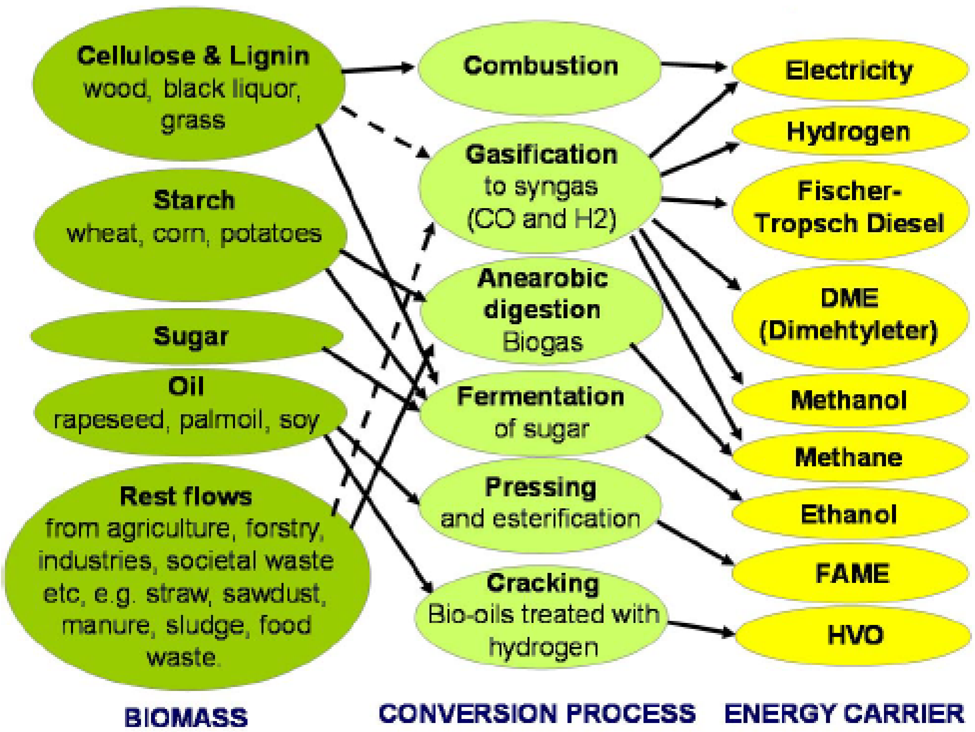

Figure 19: Example of biofuels and conversion processes

Biorefinery concepts imply conversion of incoming biomass feedstock to a variety of products, including sawn goods, pulp and paper, chemicals (bulk, intermediate and specialty), fuels and energy products.

Biorefinery processes can be integrated with different types of industrial processes, providing unique opportunities to diversify product portfolios for the host industry, thereby significantly increasing added-value from the biomass resource feedstock.

Furthermore, heat and material integration between the biorefinery process and an industrial process host site can create significant advantages for biorefinery operators, compared to stand-alone operations.

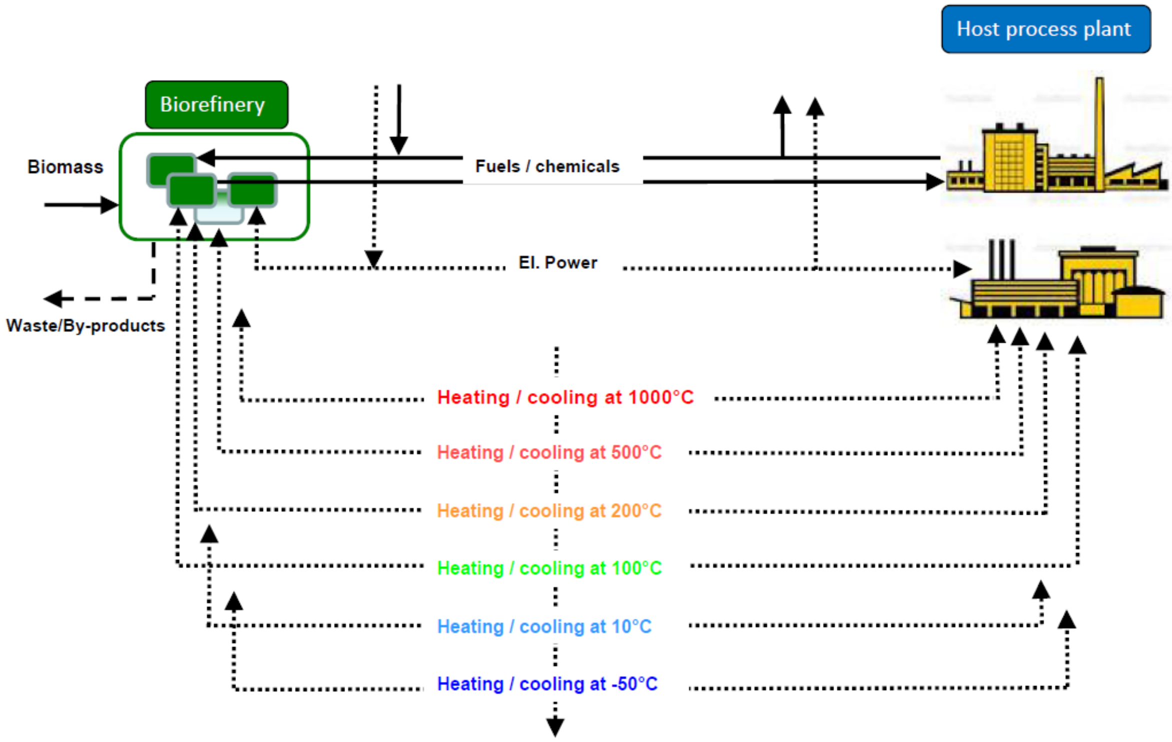

Figure 20: Co-location of biorefinery and host process plant

However, biorefinery process technology is at the development stage, and industrial decision makers are faced with the challenge of making strategic decisions about long-term implementation of such concepts. Uncertainty about future market conditions (both energy market conditions as well as market demand for new products) is significant.

In this presentation an overview of a methodology for assessing the energy gains that can be achieved by integration of biorefinery processes with an industrial host site was given.

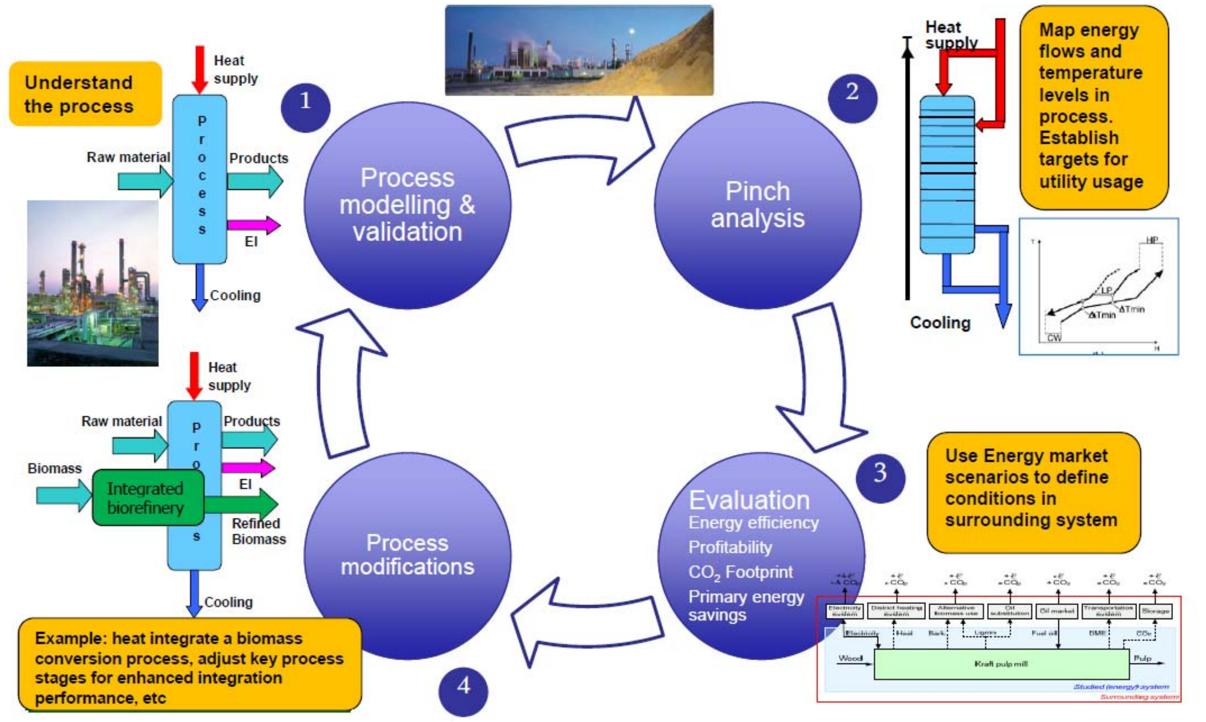

Figure 21: Maximizing biorefinery efficiency using process integration tools

Inventory of energy flow gains can then be used as input for assessing the economic performance and climate footprint reduction advantage of integrated biorefinery concepts compared to stand-alone using ENPAC, a tool for generating consistent future energy market scenarios.

The methodology and tools can be illustrated for a number of biorefinery concepts based on forest biomass feedstock gasification. The ENPAC tool takes into consideration all relevant parameters for assessing the economic and carbon footprint performance, e.g. possible future energy prices, and policy instruments, build margin technologies/performances for power, heat and biomass use.

4.2 Techno-Economic Systems Analysis of Jet Fuel and Electricity Co-Production from Biomass and Coal with CO2 Capture: an Ohio River Valley (USA) Case Study

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Globally, air transportation consumes more than 100 million tons of jet fuels annually, and the IEA expects greenhouse gas emissions from air travel to increase from about 14% of global transportation emissions in 2005 to 20% by 2050 as a result of a projected 4-fold growth in air travel.

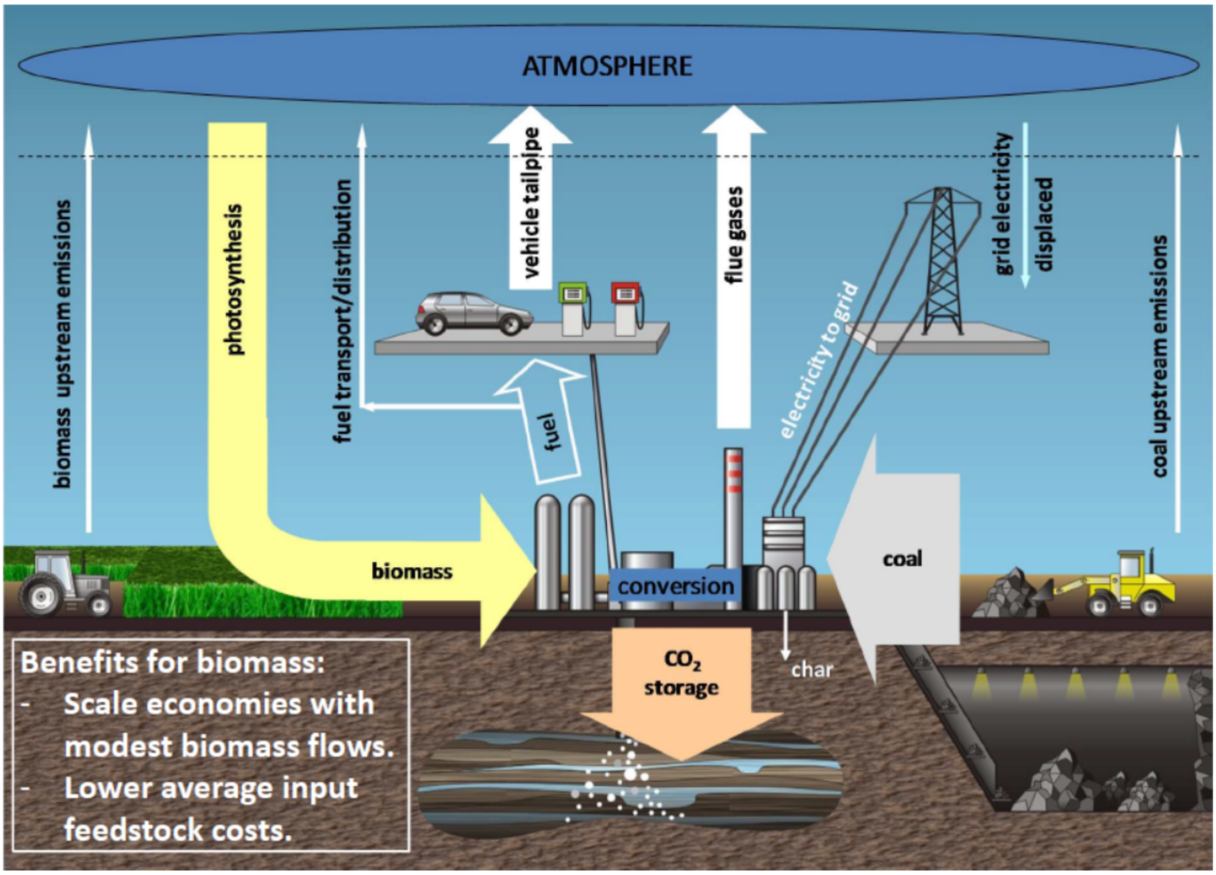

Figure 22: Co-processing biomass and coal with CCS

In the U.S. the use of petroleum-derived jet fuel is projected to increase by 14% over the next 25 years, even as projected total petroleum-derived transportation fuel use in the U.S. falls about 5%.

There are few potential low-carbon alternative fuels with the energy density and other features needed for jet aircraft. One option is co-processing of biomass and coal via gasification and Fischer-Tropsch (FT) synthesis with capture and storage of byproduct CO_2. We assess the technical, economic, and environmental viability of such plants in the next 5 to 10 years in the United States' Ohio River Valley (ORV) using bituminous coal and corn stover biomass from the region.

The impact of co-producing electricity is also examined, since new sources of electricity supply will be needed in the ORV as coal plant retirements accelerate due to new air pollution regulations. Siting co-processing plants at retired coal power plant sites will offer benefits with respect to permitting and public acceptance. Captured CO_2 is assumed to be sold into enhanced oil recovery (EOR) markets via anticipated pipeline systems connecting the ORV to oil fields in the Gulf Coast and/or the Permian Basin.

Detailed steady-state performance simulations are developed for plants that gasify coal and biomass in separate oxygen-blown reactors and convert the resulting syngas via FT synthesis and syncrude refining into synthetic jet fuel plus gasoline. Unconverted syngas and off-gases from synthesis and refining are used to fire a gas turbine combined cycle, which additionally uses heat recovered from the synthesis reactor and elsewhere to augment steam production for a bottoming steam cycle. CO_2 is captured upstream of FT synthesis, compressed to 150 bar, and sold for EOR use, as a result of which the CO_2 is permanently stored underground.

Two plant configurations are analyzed, each designed for a production capacity of about 10,000 bbls/day of synthetic jet fuel and 3,000 bbls/day of coproduct synthetic gasoline.

One plant (designated "HF" for High Fuel) exports 174 MW of electricity coproduct and the other ("CP" for Coproduction) exports more than double this amount, 393 MW. The biomass input capacity is 730 dry metric t/day, representing 5 to 7% of total feedstock input (HHV basis). Steady-state Aspen Plus process simulations provide a basis for greenhouse gas emission estimates and equipment sizing for purposes of capital cost estimation.

Estimated installed plant capital costs (in 2012$ for an "Nth plant") are $2.3 billion for HF and $2.7 billion for CP. The internal rates of return on equity (IRRE) depend sensitively on the assumed crude oil price. For projected coal purchase and grid-sale electricity prices in the ORV, the real IRRE ranges from 8.6% percent per year for either plant at $100/bbl to 14-15% per year at $125/bbl.

Considering these plants as electricity providers, the crude oil price at which electricity could be provided at the same levelized generating cost as a new baseload natural gas gas combined cycle (NGCC) is $113/bbl for CP and $109/bbl for HF. (The IRRE values at these breakeven oil prices is 11-12 percent per year.) For perspective, the levelized crude oil price over the 20-year economic lives of such plants (assuming startup in 2021) is $124/bbl according to the Reference Scenario of the USDOE/EIA *Annual Energy Outlook 2013*. CP and HF plants would have ultra-low minimum dispatch costs and so would be able to defend high design capacity factors (90%). The dispatch costs for CP and HF power plants would be less than for NGCC plants for crude oil prices as low as $40 a barrel.

A key assumption underlying the above results is the absence of a carbon mitigation policy that would effectively price GHG emissions. If such a policy were in place, CP and HF plants would probably be designed with more CO2 capture and larger biomass input fractions, and economic performance may improve substantially.

4.3 Techno-economic and Market Analysis of Pathways from Syngas to Fuels and Chemicals

Michael Talmadge, Abhijit Dutta and Richard Bain
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Advancements have been achieved in the area of producing clean synthesis gas from biomass as part of the biomass to mixed alcohols research at NREL, as well as research and development from other organizations in the industry. As the focus of research in the biofuels industry shifts away from cellulosic ethanol towards other uses of biomass for the production of advanced fuels and valuable chemicals, it is important to understand the preliminary economics and market opportunities of pathways from synthesis gas to fungible fuels and chemicals. This understanding can guide the new research directions and objectives.

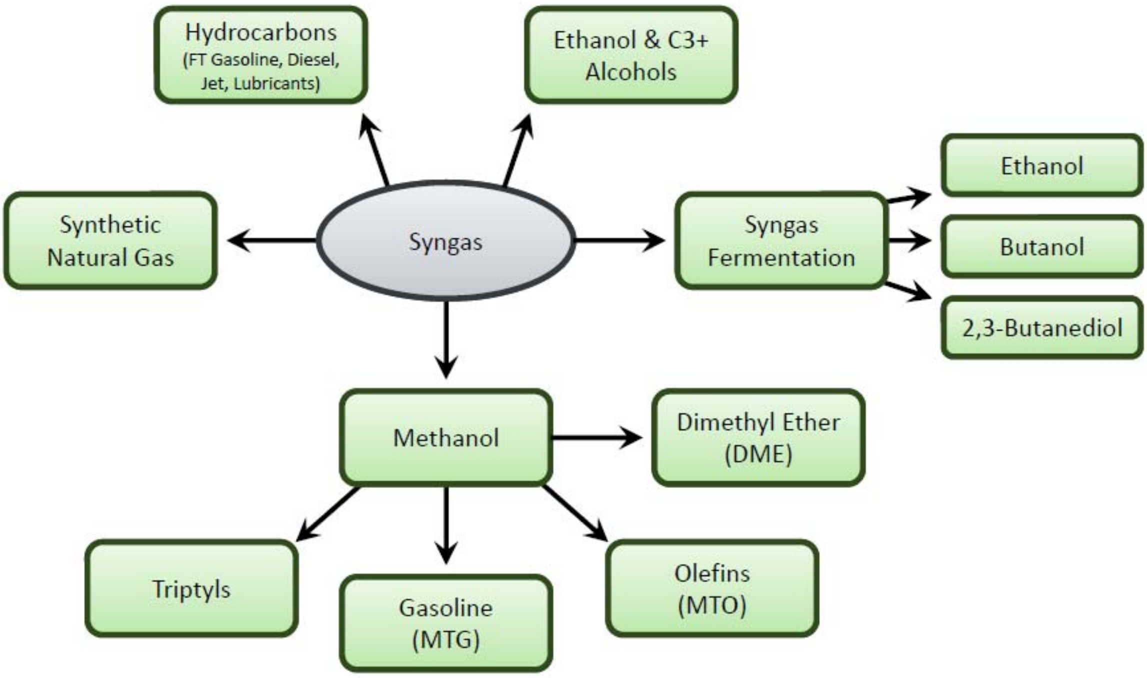

Figure 23: Fuel pathways explored

This presentation focused on the techno-economic analysis of pathways to fuels and chemicals from biomass-derived synthesis gas. The study identifies promising research routes from synthesis gas by assessing cost viabilities of process pathways relative to market pricing history.

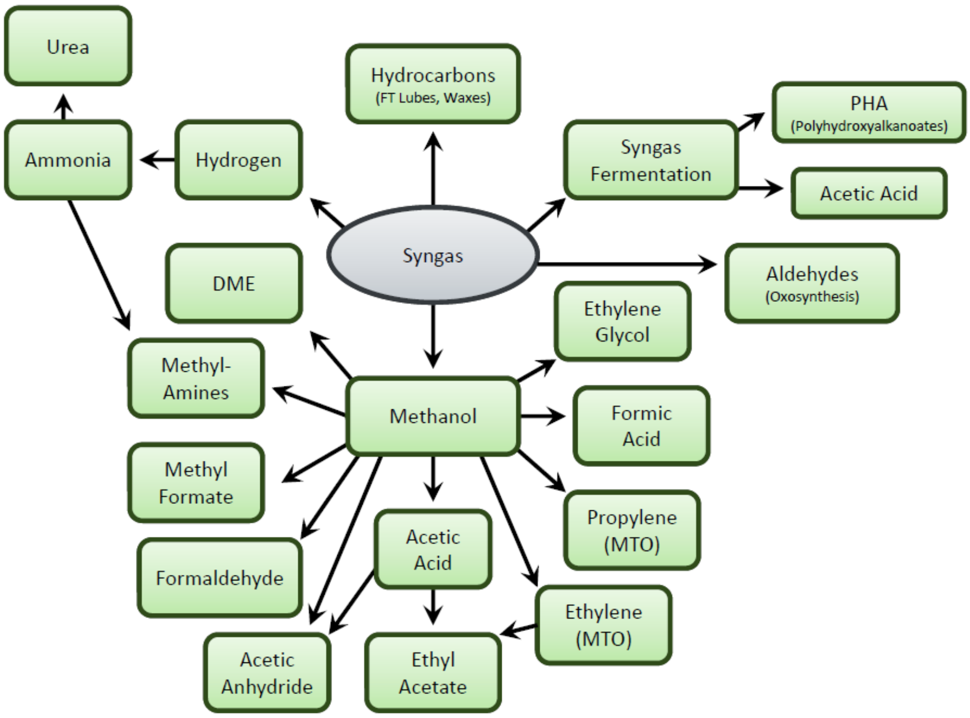

Figure 24: Chemicals pathway explored

The analysis builds an understanding of the economics of potential biomass-derived synthesis gas pathways by assessing the following:

1. *Synthesis gas costs*

Synthesis gas serves as the basis for this analysis as the feedstock for future fuels and chemicals pathways. Prior to assessing the routes from synthesis gas, it is critical to understand the predicted cost of the biomass-derived intermediate. The estimated cost of gasification-based synthesis gas is presented as a function of H_2 to CO ratio and required downstream supply pressure.

2. *Techno-economics from literature*

This assessment is based on published literature for currently researched pathways from biomass including synthetic natural gas (SNG), alcohols, hydrocarbons, hydrogen, and methanol and its derivatives. Economic and process parameters reported in the literature sources serve as the basis for techno-economic estimate.

The literature parameters, along with the cost of the process feedstock (synthesis gas), are combined with a consistent set of techno-economic assumptions for estimating a minimum product selling price ranges for each pathway in pioneer plant and nth-plant scenarios. The resulting minimum product selling prices are compared to the market pricing history for each corresponding fuel and chemical. Market capacities for the fuels and chemicals are also considered in the analysis to quantify potential impact from market penetration of biomass-derived equivalents. The analysis results provide valuable insights into potential pathways for fungible products from biomass derived syngas and options for future research focus.

4.4 Negative Emissions to Meet the Global Carbon Budget: Necessity and Opportunities for Bio-CCS Concepts

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A negative carbon dioxide emission or negative emission or a process that is carbon negative gives a permanent removal of the greenhouse gas carbon dioxide from Earth's atmosphere. It is considered the direct opposite of carbon dioxide emission, hence its name. It is the result of carbon dioxide removal technologies, such as bio-energy with carbon capture and storage, biochar, direct air capture or enhanced weathering (Wikipedia).

The following table offers an overview of CO_2 storage and capture deployment for different scenarios.

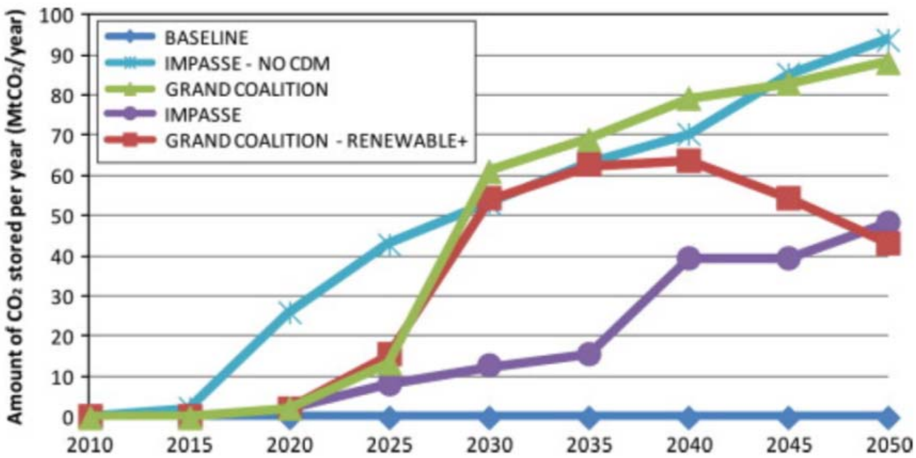

Figure 25: CO_2 storage and capture deployment for different scenarios (Source: van den Broek et al., Energy Policy, 2011)

Summary of the presentation

- CCS and bio-CCS are an essential part of desired global GHG mitigation strategies
- Within such strategies the role of coal will diminish, but (co-fired) PC and (P/I)GCC +CCS can provide key platforms for large scale bio-CCS on medium term
- Short term co-firing and building capacity for large scale sustainable biomass supplies is a vital stepping stone
- Can provide remarkable low mitigation costs and much needed flexibility on short to medium term

Summary

The aim of this workshop was to initiate a dialogue across the technology/system interface between IEA Bioenergy Task 33 (thermal gasification of biomass) and IEA Industrial Energy-Related Technologies and Systems (IETS) Annex XI (industry-based biorefineries), as well as on methods and results for technical, economic and environmental evaluations of integrated biomass-based gasification systems. The other aim was to identify topics for further international cooperation in these areas.

Over 50 experts participated on the workshop, which was divided into 4 sessions to cover all the areas of biomass gasification, system and integration aspects:

- Session 1: **Biomass Gasification to Fuel Gas; Integration into Power and CHP**
- Session 2: **Biomass Gasification into Syngas Part I; Upstream and Internal Integration**
- Session 3: **Biomass Gasification into Syngas Part II; Downstream and Product**
- Session 4: **Methodologies for Assessing Techno-economic Performance and Climate Impact**

All the presentations given on the workshop can be found at the Task 33 website, **www.ieatask33.org.**