



Ammonia from Biomass Gasification

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Citation for published version (APA):

Gilbert, P., Thornley, P., Alexander, S., & Brammer, J. (2009). Ammonia from Biomass Gasification. In *host publication*

Published in:

host publication

Citing this paper

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Conference: International Conference on Polygeneration Strategies

Date and Location: 1st-4th September 2009, Vienna

Title: Biomass gasification for ammonia production

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Objective: The main aim of the conference was to present the current state-of-the-art of syngas production, syngas cleaning and syngas utilization. Furthermore, it offered a platform for exchange of information, results and experiences as well as networking. For more information visit www.icps09.org.

Abstract

109 million tonnes of ammonia is produced globally each year, 85% of this is synthesised from combining H₂, produced from steam reforming of natural gas, and nitrogen separated from air. The process is very energy intensive and releases 208 million tonnes of CO₂. Production of ammonia from renewable resources, such as biomass, could substantially reduce this. One option is to gasify biomass to produce a hydrogen rich syngas for ammonia production. This paper reviews currently available gasification technologies to assess the viability of ammonia production using this method, and identifies those most suitable for further analysis. The gasifier selection is based on the following criteria: syngas composition, efficiency, operating conditions, scale and biomass track record. Potential process schemes are presented with preliminary mass/energy and greenhouse gas balances to estimate the potential value of developing such a system. Critical issues are identified in the overall system, from biomass cultivation to ammonia production. These issues need to be evaluated further via economic and life cycle assessment techniques.

1. Introduction

Ammonia is a fundamental chemical compound required for the production of nitrogen based fertilisers for agriculture, horticulture and biomass. The conventional method in producing ammonia is the Haber-Bosch process, which combines H₂ from steam reforming of natural gas and N₂ from the air. 109 million tonnes of ammonia is produced globally each year and the steam reforming process is very energy intensive, accounting for 1.2% of the global primary energy demand (Ahlgren, Baky et al. 2008). Life cycle assessments have shown that fertiliser production can be responsible for up to 80% of the total greenhouse gas emissions associated with biomass cultivation systems (Elsayed and Mortimer 2001). Consequently, there is interest in reducing the environmental impact of fertiliser production, by minimising the input of fossil fuels. It is proposed that this could be achieved through utilising renewable technologies such as bioenergy systems.

Thermal conversion technologies appropriate for producing hydrogen from biomass include gasification and pyrolysis, where a hydrogen rich syngas could replace the input of natural gas required for ammonia production. Anaerobic digestion could yield a methane feed, which could then be converted to hydrogen in a similar fashion to the conventional natural gas approach. Other biological advancements are reviewed elsewhere (Ni, Leung et al. 2006). Nonetheless, the focus of this study is biomass gasification.

In Europe, ammonia plants are large scale systems and typical sites operate at 1000-1500 t/d, however more recent plants can be in excess of 1800 t/d (EFMA 2000a). These large scales are driven by the scale economies of the high-pressure Haber-Bosch process and the associated air separation plant for nitrogen supply. They require a natural gas input of 23.4 MJ per kg of ammonia (EFMA 2000a). The scale of the proposed biomass-based plant will need therefore to be commensurate, but will in practice be constrained by the supply of biomass and by the scale of the gasification reactor. Preliminary calculations we have carried out indicate that 1500 t/d of ammonia would require a minimum of about 2000 dry t/d biomass. The largest operating biomass gasifier to date consumes about 350 dry t/d biomass (Barber and Warnken 2008) and new plant proposals commonly specify up to double this scale. Coal gasifiers are now being designed at over 3000 t/d. Scale may also be limited by biomass supply logistics; although a planned port-located biomass combustion plant in the UK will process 5000 dry t/d of imported biomass (SKM 2006). Therefore it is possible that a biomass-based ammonia plant could achieve a production rate comparable to natural gas plants given the right scenario.

The longer-term objective of this study is to determine the environmental and techno-economic impacts of producing biomass derived ammonia and fertiliser compared to conventional ammonia production from natural gas. In this preliminary paper greenhouse gas balances will be calculated to identify potential savings for a candidate overall process scheme. Short rotation coppice (SRC) willow will be cultivated and used as feed for gasification, whereby the gasifier is selected for its scale-up and H₂ producing attributes. The product gas will be conditioned to maximise the hydrogen content, and if necessary further nitrogen will be added to achieve the correct molar ratio of 3:1. Ammonia production will then take place in a similar way to conventional ammonia production.

2. Methodology

The feasibility of producing ammonia from biomass gasification is to be assessed using life cycle assessment (LCA) and techno-economic analysis (TEA).

2.1 Life Cycle Assessment

LCA is a methodology used to assess the environmental impact of a product or process from cradle-to-grave. The principles and framework of LCA are described in ISO 14040:2006 (ISO 2006). SimaPro 7.1, developed by Prë Consultants, is used to determine the environmental impacts of the biomass scenarios compared to conventional ammonia production (Goedkoop, Schryver et al. 2008). Ecoinvent is

used as a reference for the life cycle inventory data and for the impact assessment methodology. The four sections of an LCA study are: goal and scope of definition, inventory analysis, impact assessment and interpretation.

2.2 Techno-Economic Analysis

The TEA analyses the technical and economic feasibility of a specified system, which in the case of this study will be the numerous biomass gasification processes currently available. There are several methods of analysis though the preferred, as outlined by sources such as (Bridgwater, Toft et al. 2002), is to divide the production process into specific steps and economically evaluate each section separately. Not only does this outline which areas of production require the largest financial input but it also highlights any economic indicators that were not originally considered. The areas currently being considered are feedstock preparation, gasification, gas cleaning and ammonia production.

It is being assumed that all feedstock types enter the gasifier in the same state; hence pre-treatment has to be considered with additional cost. Oxidising agent selection can give rise to a high economic impact, either by entailing an upfront cost increase at the gasification stage or throughout gas cleaning and ammonia production. The TEA will establish the capital investment and cost of ammonia production for each process route at a range of scales. These will then be compared to conventional ammonia production processes.

3. System Characterisation for Ammonia Production

3.1 Conventional Ammonia Production

The reference case for this study is conventional ammonia production, which is standard practice within industry and is described in detail by the European Fertilizer Manufacturers Association (EFMA 2000a). The two main types of ammonia production are steam reforming of natural gas or the partial oxidation of heavy fuel oil. The latter technique could be transferred to utilising fast pyrolysis oil. Coal gasification and water electrolysis are no longer used for ammonia production in Europe. The process scheme for ammonia production from steam reforming of natural gas has been selected as the preliminary reference case and is displayed in Figure 1.

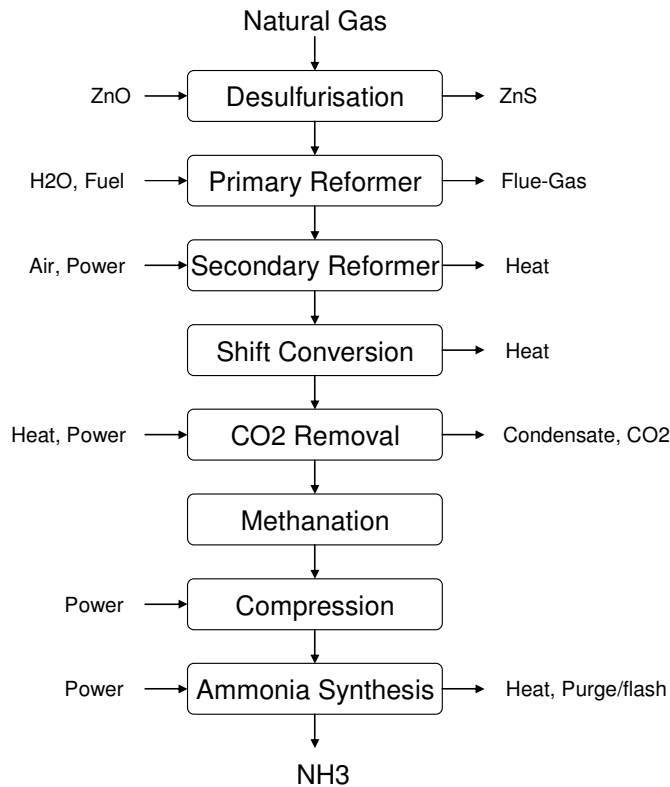


Figure 1: Schematic of the Steam/Air Reforming Process (EFMA 2000a)

From an LCA perspective, the significant environmental impacts of conventional ammonia production stem from the use of fossil fuels – natural gas as the feedstock and heavy fuel oil as the fuel for reforming. The large consumption of natural gas results in considerable CO₂ emissions during steam reforming and shift conversion increasing global warming potential (GWP). Approximately 1.5 kg of CO₂ is emitted to the atmosphere per kg of ammonia produced (Althaus, Chudacoff et al. 2007). CO₂ emissions can be reduced through effective recovery however this depends on the downstream facilities. The second major source of emissions arises from the flue-gas in the primary reformer through using heavy fuel oil and could potentially lead to a notable impact on ozone layer depletion (ODP). This could be reduced by burning bio-diesel or additional syngas produced via biomass gasification. Finally during operation, emissions of ammonia to water from condensates and scrubbing of waste gases increases the impact from eutrophication and the likelihood of human and aquatic toxicity.

3.2 Ammonia Production from Biomass

The biomass gasification system involves the cultivation of biomass, gasification and syngas cleaning, syngas conditioning and ammonia production. Utilising biomass gasification will address the environmental impacts of ammonia production by reducing the need for fossil fuels. Consequently, the GWP and ODP should be lower. The process scheme is shown in Figure 2. Syngas conditioning is regarded as the stages involved from desulphurisation to compression in Figure 1. However, since the H₂ content will be higher from biomass gasification, it is thought that reduced power and heat demand will be required – increasing the conversion efficiency to ammonia.

Furthermore, as the sulphur content from biomass gasification will also be lower, the desulfurization step could be discounted. Only the significant impacts have been included in Figure 2, as every stage will involve the release of CO₂.

3.3 Overview of Process Schemes for Ammonia from Biomass

3.3.1 Willow Cultivation, Processing and Delivery

The willow cultivation scheme is based on Thornley, Upham et al. 2009 (Thornley, Upham et al. 2009). Referring to the first three sections of Figure 2, willow is cultivated near the gasification plant on previously arable land. At the start of ground preparation, herbicide is applied to kill perennial weeds. Tillage is then completed to cultivate the land so to become suitable for planting. Willow is established from lengths of willow cane and is obtained from nursery production at local level. 15,000 willow cuttings are required to produce 29.4 odt/ha at every 3 year harvest, with a moisture content of 50%. As a result, the average annual yield is 19.6 t/ha, as received. Harvesting is done with a self-propelled forage harvester with a specialist SRC header to produce 35mm wood chips. The chips are blown from the harvester into a trailer and transported to the storage area for drying. Drying reduces the moisture content from 50% to 30%. The chips are transported by 28 t lorry to the gasification plant. Sewage sludge cake is applied at a rate of 20 t/ha every three years after harvest, which is common practice for large scale sites in the UK. After cultivation, the land is returned to its original condition.

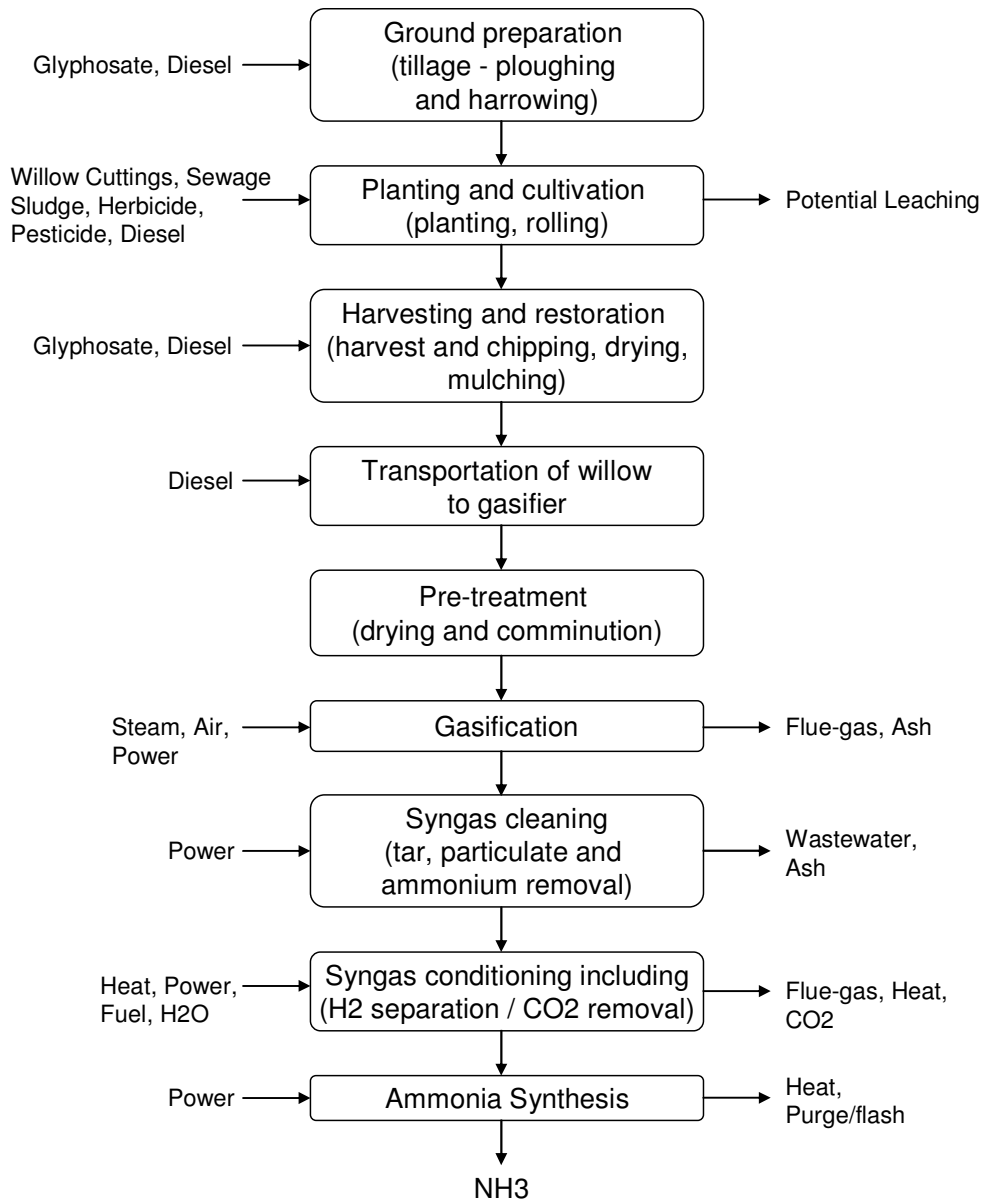


Figure 2: Schematic of Ammonia Production from Biomass Gasification

3.3.2 Potential Biomass Gasification Technologies

Currently available gasification technologies were reviewed to assess the viability of ammonia synthesis gas production and are shown in Table 1 and the different technologies available are discussed below. Following gasification, either hot or cold gas cleaning will remove particulates and recycle solids and tars. To achieve a high H₂ yield the syngas will be conditioned as described in section 3.3.3. The criteria used to assess the gasifiers were: syngas composition, efficiency, operating conditions, scale and biomass track record.

Table 1: Review of Existing Gasifiers for Ammonia Production from Biomass

Gasifier	Fuel	Syngas Composition (mol.%)	LHV (MJ/m ³)	Efficiency	Operating Conditions	Scale	Hours
FICFB, Gussing ^a	Biomass	39% H ₂ , 20% CO, 27% CO ₂ , 14% CH ₄	14	73% _{gasifier} , 25% _e	Twin circulating fluidised bed, steam/air, 850°C	8MW _{input} (4.5MW _{th} , 2 MW _e)	6,500+
SilvaGas ^b	Biomass	17.5% H ₂ , 50% CO, 9.4% CO ₂ , 15.5% CH ₄	18.5	40% _e	Twin circulating fluidised bed, steam/air, 850-1000°C	10 t/day, 200 kW _e	20,000
SilvaGas ^b	Biomass	22% H ₂ , 44.4% CO, 12.2% CO ₂ , 15.6 % CH ₄	17.3	40% _e	Twin circulating fluidised bed, steam/air, 850-1000°C	182 odt/day, 50MW _e	-
Foster Wheeler, Sydkraft ^c	Biomass	9.5-12% H ₂ , 16-19% CO, 14.4- 17.5% CO ₂ , 5.8-7.5% CH ₄ , 48- 52% N ₂	5.3-6.3	32% _e , 83% _{net}	Circulating fluidised bed, air, 950-1000°C	18MW _{input} , 6MW _e , 9MW _{th}	8,500
FW CHRISGAS ^d	Biomass	11.79% H ₂ , 11.86% CO, 27.92% CO ₂ , 8.17% CH ₄	5	32% _e , 83% _{net}	Circulating fluidised bed, steam/oxygen, pressurised, 950-1000°C	18MW _{input} , 6MW _e , 9MW _{th}	-
Shell ^e	Coal	28.8% H ₂ , 63.8% CO, 2% CO ₂	10.9	-	Entrained flow, oxygen, pressurised, 2000°C	192 MW _{gross}	-
Texaco ^f	Coal	37% H ₂ , 39% CO, 21% CO ₂	9.1	-	Entrained flow, oxygen, pressurised, 1250- 1550°C	900kW _e	-
E-Gas ^g	Coal	-	-	-	Two-stage entrained flow, oxygen, pressurised, 1400°C	262 MW _e	Demonstrated
British Gas Lurgi ^h	Coal	29% H ₂ , 54.6 % CO, 2.4% CO ₂ , 7.1% CH ₄	12.0	-	Fixed bed, steam/oxygen, pressurised, 570- 1100°C	-	-
High Temp Winkler ⁱ	Coal	-	-	-	Fluidised bed, pressurised, 800-1000°C	-	Co-fire demonstrated

^a (Felder 2004; Hofbauer 2006; Jungbluth, Dinkel et al. 2007; Hofbauer, Rauch et al. b)

^b (Paisley and Overend; Paisley and Welch 2003)

^c (Stahl and Neergaard 1998; Stahl, Waldheim et al. 2004; Palonen, Anttikoski et al. 2006)

^d (Stahl, Waldheim et al. 2004; Albertazzi, Basile et al. 2005)

^e (Doctor, Molburg et al. 2001b; Zheng and Furinsky 2005)

^f (Richards 1995; Hornick and McDaniel 2002; Zheng and Furinsky 2005)

^g (Dowd 2000)

^h (Cooke and Taylor 1993; Shelton and Lyons 2000; Zheng and Furinsky 2005)

ⁱ (Renzenbrink, Wischniewski et al.; Adlhoch, Sato et al. 2000)

Twin Fluidised Bed Gasification

The two types of twin-reactor fluidised beds considered were SilvaGas, developed at FERCO Enterprises and the Fast Internal Circulating Fluidised Bed gasifier (FICFB), developed at the University of Vienna.

The FICFB gasifier at Gussing operates as a two stage reactor, with a gasification zone and a combustion zone. Biomass is gasified to produce a syngas and the non-volatile components (char) are transferred with the bed material into the combustion zone, where they are burnt completely. Heat from the combustion zone is transferred to the gasification zone to maintain the gasification process. The 100 kWth pilot plant was developed over 5 years in Vienna and extensive testing (1,600 hours) was performed to determine the effect of temperature, steam/biomass ratio and bed catalyst (Hofbauer, Rauch et al. a). Steam is used as the gasifying agent in the gasification zone and gasification takes place at 850°C. Utilising steam results in a low-nitrogen and low-tar syngas (1.5-2.5 g/Nm³) prior to gas cleaning. Biomass feedstock and moisture content could vary, and the gasifier has operated using wood chips, annual crops and C4-energy crops, with moisture content ranging between 15-40%. With a biomass moisture content of 15 % and a cold gas efficiency of 73 %, the syngas composition is promising for H₂ production (39 % mol_{dry}) (Jungbluth, Dinkel et al. 2007). A wood-chip fired 8 MWth demonstration plant was constructed in 2001 and at the end of April 2005, 6,500 hours of gasifier operation was recorded (Van der Drift; Hofbauer, Rauch et al. b). Of the 8 MW fuel input, 4.5 MWth will be used for district heating and 2 MWel will be the electrical output. The electrical efficiency is 25% and the total efficiency is 80% (Hofbauer 2006).

The SilvaGas gasification system operates similar to the FICFB gasifier. Nonetheless, biomass is gasified in a higher temperature region at 850-1000°C producing a medium heating value syngas (17-19 MJ/Nm³) (Paisley and Welch 2003). The biomass track record is positive and the heating value and syngas concentration remain constant with varying biomass feed. Testing of the Silvagas gasifier in the 10 ton per day Process Research Unit was successful and over 20,000 hours operation was reported (Paisley and Overend). The gasifier has been tested at a commercial scale demonstration site at Burlington, Vermont and was designed for 182 dry tonnes (200 tons) per day of biomass feed. The moisture content of the wood feed ranged between 10-50% and operating at the larger scale site, the equivalent heating value was reported lower at 11-14 MJ/Nm³.

Circulating Fluidised Bed Gasification

Fluidised bed gasifiers have been used extensively within the coal industry, providing uniform reactor temperatures and increased thermal efficiency compared to fixed bed gasifiers. The other advantages include high carbon conversion, good scale-up potential, efficient tar conversion and the production of a medium LHV syngas (Belgiorno, De Feo et al. 2003).

Sydskraft AB produced the worlds first complete biomass fed IGCC power plant using a pressurised CFB Foster Wheeler gasifier (Stahl and Neergaard 1998). The air-blown

gasifier operated at 950-1000°C and at approximately 20 bar. Biomass fuel was inputted at 18 MW (equivalent of 4 t/hr) with a moisture content of 5-20%, which was pre-dried using the flue gas from the gas turbine. As a result, the plant produces 6 MWe and 9 MWth with a net electrical efficiency of 32% and total net efficiency of 83%. Due to utilising air as a gasifying agent, the heating value of the syngas was 5.3-6.3 MJ/Nm³. The process could be optimised by increasing the O₂ content through enriched air gasification (Campoy, Gómez-Barea et al. 2009). Tests performed using a bubbling fluidised bed gasifier have shown that increasing the O₂ content from 21% to 40% (v/v) increased gasifier efficiency from 58% to 68% and the H₂ content from 8.7% to 27.5%.vol dry basis. The costs were relatively low compared to utilising O₂/steam gasification.

The CHRISGAS Project is an expansion on the original Varnamo gasification demonstration plant, aiming to produce H₂-rich syngas from biomass (Stahl, Waldheim et al. 2004). The gasifier operates at elevated pressures using steam and O₂ as gasifying agents (Albertazzi, Basile et al. 2005). An oxygen blown gasifier would integrate well with the requirement for an Air Separation Unit (ASU) to supply N₂ to the ammonia synthesis plant. Still more attractive would be to supply the gasifier with enriched O₂ air rather than pure O₂; the former being much easier and cheaper to supply from the Air Separation Unit (ASU). By an appropriate choice of O₂ concentration, the synthesis gas could be delivered with the correct N:H molar ratio. Pressurised gasification is also attractive, as it integrates well with the gas conditioning process which for natural gas is commonly operated at 30 bar prior to ammonia synthesis at 60-180 bar.

The high-temperature Winkler (HTW) process is a fluidised bed coal gasification process and operates under pressure at 800-1000°C (Renzenbrink, Wischniewski et al.). HTW gasification could be suited for biomass feeds (Adlhoch, Sato et al. 2000). Co-gasification of pre-treated municipal solid waste (1000 tons) was demonstrated on a commercial scale at Berrenath, Germany.

Entrained Gasification

Entrained gasifiers have been used extensively for coal gasification and successful systems include the Texaco, Shell and E-Gas gasifiers. There has been limited research into the successful application of biomass fed entrained gasifiers at demonstration scale. The performance of four coal fed IGCC plants utilising Shell, Texaco, British Gas Lurgi and Kellogg Rust Westinghouse gasifiers have been assessed using Aspen Plus (Zheng and Furinsky 2005). The operating conditions of the gasifiers are provided in Table 1.

The Shell gasifier receives dry coal feed and is oxygen blown, however does not have a proven biomass track record (Doctor, Molburg et al. 2001b; Zheng and Furinsky 2005).

The Texaco gasification process has been installed at the Tampa Electric Polk Power

Station for IGCC (Hornick and McDaniel 2002). Texaco state that the syngas could be used for high-purity H₂ and ammonia production. Biomass co-firing has been reported; however, the biomass would have to be prepared in a similar way to coal through milling to a fine powder to allow injection into the reactor. During the test period the biomass yielded 860 kW (7700 kWh total), based on heating values and flow rates of biomass and base fuel.

The E-Gas is a coal fed, continuous slagging, two-stage entrained flow gasifier. A 262 MWe Wabash River Coal Gasification Project has been successfully demonstrated (Dowd 2000). The gasifier has not been tested with biomass.

Fixed Bed Gasification

Updraft and downdraft fixed bed biomass gasifiers were not assessed in depth, as they offer little control and scale-up attributes (Belgiorno, De Feo et al. 2003). Furthermore, the conversion of tar is reported to be low in updraft gasifiers. Nonetheless, the British Gas Lurgi (BGL) gasifier was reviewed. It is an oxygen/steam blown, fixed bed gasifier (Cooke and Taylor 1993; Shelton and Lyons 2000).

Choice of gasification technology for further analysis

The FICFB gasifier was selected as a candidate gasifier for preliminary analysis, as it has received successful testing with steam gasification to produce a high H₂ content syngas prior to CO₂ removal. Additionally, the pilot plant is still in operation. Extensive information on the FICFB gasifier is available online and Ecoinvent life cycle inventory data has been published using mass and energy data based on the Gussing plant (Reinhard 2000; Jungbluth, Dinkel et al. 2007). Alternative process routes incorporating other gasifiers, gas conditioning options and ASU arrangements will be selected in due course and evaluated through careful LCA and TEA.

3.3.3 Syngas Conditioning

Three options were identified as potential methods to separate hydrogen from the syngas: CO₂ removal, Pressure Swing Adsorption (PSA) and Ceramic Membranes. Prior to the hydrogen separation step, the primary reformer converts methane and higher hydrocarbons in the syngas to H₂ and CO and the shift reactor converts CO to H₂ through the exothermic water gas shift reaction (Koroneos, Dompros et al. 2008). In natural gas plants, these processes are commonly operated at around 30 bar.

CO₂ removal

In conventional ammonia plants, syngas is passed through a reformer and shift reactor to produce a H₂ rich synthesis gas (Hamelinck and Faaij 2002). CO₂ is removed in either a chemical or physical absorption process, and traces of CO₂ and CO are then converted to CH₄ through methanation and removed. In the chemical absorption process, aqueous amine solutions are typically used, but are not regarded as the best available technique, as the regeneration requires a large amount of energy. New

ammonia plants utilise the Activated Methyl DIethanolamine (aMDEA) standard 2-stage process (EFMA 2000a). Hydrogen content can have a purity of up to 98 %, with the remainder comprising typically of N₂.

CO₂ removal through chemical absorption with biomass gasification has been the subject of previous studies (Corti and Lombardi 2004; Carpentieri, Corti et al. 2005). The extent that CO₂ emissions were reduced in a biomass combined gasification cycle was determined using performance analysis and LCA. Nonetheless, the focus of these studies was not to maximise hydrogen yield. Since the ammonia synthesis from biomass will be similar to conventional synthesis from natural gas, critical issues to ensure successful conversion include the clean-up steps for tar, sulphur and ash prior to reforming.

Pressure Swing Adsorption

To improve H₂ purity, pressure swing adsorption (PSA) should be considered as an alternative to CO₂ removal. PSA is based on the different adsorption characteristics of different molecules. The process passes the H₂ rich synthesis gas over several beds, which in turn extract impurities, CO₂ and H₂O. The resultant syngas is extremely pure and H₂ yield can be as high as 99.999% (Hamelinck and Faaij 2002). If all the gas is not converted it can be recycled after passing through the beds. However, recycled gas requires recompression and cooling, which will increase capital and operational costs.

Ceramic Membrane

Ceramic membranes are an attractive option for H₂ separation, as they combine shift and separation in one reactor – simplifying the design requirements. The technology relies on the mobility of compounds through a surface, based on a difference between the partial gas densities. Furthermore, the physical and chemical interaction of the gases with the membrane will affect the rate at which they are transported through. The use of membranes for H₂ separation is currently an advanced option (Page 7 from (Hamelinck and Faaij 2002)). Hamelinck and Faaij go on to discuss the removal of the shift reactor due to the membrane surface catalysing the water gas shift reaction – although data released on this was stated as being largely confidential.

Ceramic membranes are capable of operating over a wide temperature and pressure range, and are easier to manufacture compared to PSA technologies. In addition, with a reduction in the requirement for heat exchangers, efficiency losses are reduced and capital costs are lower ((Williams 1998) from (Hamelinck and Faaij 2002)). In a LCA study to determine the feasibility of producing ammonium nitrate fertiliser from biomass, ceramic membranes were utilised to separate hydrogen (Ahlgren, Baky et al. 2008).

To produce a hydrogen rich feed for ammonia synthesis, CO₂ removal was chosen for this preliminary analysis. CO₂ removal was regarded as being established and proven, and could operate at the required scale to produce an adequate feed of H₂. PSA would result in increased costs for the system, and ceramic membranes were considered to

be in the developing stages, therefore would not be a true representation of the current best available technologies. They may be evaluated later in the work programme.

3.3.3 Ammonia Synthesis

Once the syngas is fully conditioned and contains the required purity of H₂ (together with up to the correct amount of N₂ in some process configurations), it is necessary to add the necessary remaining N₂ to achieve the correct molar ratio (supplied from the ASU) and then proceed to the ammonia synthesis step. This is the well-known Haber-Bosch process, commonly operated at between 60 and 180 bar and thus requiring the synthesis gas to be compressed.

4. Mass and Energy Balances

A preliminary mass and energy balance was completed. At a conventional ammonia production plant, 35.1 GJ of natural gas feedstock is required to produce 1500 t/d of ammonia (Althaus, Chudacoff et al. 2007). Considering the biomass scenario, the H₂ content in the syngas is higher than the H₂ content in natural gas. Consequently, the process should be more efficient in converting the syngas into H₂ during conditioning. Using the Gussing syngas composition in Table 1, and assuming a gasifier cold gas efficiency of 73% and syngas net heating value of 14 MJ/Nm³ (Jungbluth, Dinkel et al. 2007), a minimum of 2000 t/d dry biomass is required to produce 1500 t/d of ammonia. This assumes that H₂ conversion is maximised in the reformer and all the CO is converted to H₂ during the water gas shift reaction. In reality, this will not be the case, and LCA and TEA is therefore required to produce a detailed mass and energy balance to understand the environmental impacts and technicalities of the process. This will be the focus of the work programme within Supergen Bioenergy.

5. Environmental Impacts

5.1 Greenhouse Gas Balance

Switching to a H₂ rich feedstock from biomass gasification will reduce the impact of CO₂ emissions by minimising natural gas input. Therefore, the resultant GWP will be lower from ammonia synthesis. If bioenergy is used as the fuel for the primary reformer, GWP and ODP impacts will reduce further. The main contributors for GHG emissions will now stem from biomass cultivation and gasification. Nitrous oxide emissions from applying fertilisers to the soil, and the use of diesel for the operation of agricultural machinery and tractors during cultivation will be significant (Ahlgren, Baky et al. 2008). Furthermore, transportation of inputs required for cultivation and gasification, and delivery of willow to the plant will increase the GWP. As ammonia produced from biomass may operate at a smaller scale, expected plant output will be investigated to determine its effect on GHG emissions. TEA will look at different scales of operation to establish the most economic configurations and the GWP of the most promising will be evaluated.

5.2 Other Environmental Impacts

The other environmental issues that will be identified through LCA are acidification,

eutrophication, abiotic depletion and human and fresh water toxicity. The levels of eutrophication and acidification are expected to increase due to cultivation, in comparison to using natural gas (Heller, Keoleian et al. 2003; Brentrup, Küsters et al. 2004b; Ahlgren, Baky et al. 2008). From initial LCA work, nitrogen and phosphorous leaching from the sewage sludge application are thought to contribute the most to eutrophication, and acidification potential is thought to increase from nitrous oxide emissions from the use of diesel in the tractors. Evaluation of other cultivation strategies will therefore also be evaluated, possibly including utilisation of the biofertiliser for biomass growth. Increasing the intensity of biomass cultivation will result in higher NH_3 emissions to soil (Brentrup, Küsters et al. 2004b). Finally, careful consideration must be taken for the environmental impacts occurring from the disposal of ash from the gasifier.

6. Conclusions

Existing gasifiers and gas conditioning technologies were reviewed for ammonia production from biomass gasification. The FICFB gasifier with CO_2 removal was selected as the preliminary strategy suitable for producing a hydrogen rich syngas. Detailed LCA should now be completed, as the preliminary calculations suggest that considerable savings could be made on greenhouse gas emissions, arising from the reduced usage of fossil fuels. Furthermore, LCA would highlight the potential environmental impacts of acidification and eutrophication from the use of fertilisers and pesticides during biomass cultivation. The next stage of work will focus on completing mass and energy balances and greenhouse gas balances of the selected process scheme to develop a detailed LCA and TEA.

References

- Adlhoch, W., H. Sato, et al. (2000). High-temperature Winkler gasification of municipal solid waste. 2000 Gasification Technologies Conference, San Francisco, California.
- Ahlgren, S., A. Baky, et al. (2008). "Ammonium nitrate fertiliser production based on biomass - Environmental effects from a life cycle perspective." Bioresource Technology **99**(17): 8034-8041.
- Albertazzi, S., F. Basile, et al. (2005). "The technical feasibility of biomass gasification for hydrogen production." Catalysis Today **106**(1-4): 297-300.
- Althaus, H., M. Chudacoff, et al. (2007). Life Cycle Inventories of Chemicals, Final Report Ecoinvent v2.0 No. 8. Duebendorf, CH, Swiss Centre for Life Cycle Inventories.
- Barber, M. and M. Warnken (2008). Biomass Technology Review: Processing for Energy and Materials, Crucible Carbon.
- Belgiorno, V., G. De Feo, et al. (2003). "Energy from gasification of solid wastes." Waste Management **23**(1): 1.
- Brentrup, F., J. Küsters, et al. (2004b). "Environmental impact assessment of agricultural production systems using the life cycle assessment (LCA) methodology II. The application to N fertilizer use in winter wheat production systems." European Journal of Agronomy **20**(3): 265-279.
- Bridgwater, A. V., A. J. Toft, et al. (2002). "A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion." Renewable and Sustainable Energy Reviews **6**(3): 181-246.
- Campoy, M., A. Gómez-Barea, et al. (2009). "Air-steam gasification of biomass in a fluidised bed: Process optimisation by enriched air." Fuel Processing Technology **90**(5): 677-685.
- Carpentieri, M., A. Corti, et al. (2005). "Life cycle assessment (LCA) of an integrated biomass gasification combined cycle (IBGCC) with CO₂ removal." Energy Conversion and Management **46**(11-12): 1790-1808.
- Cooke, B. H. and M. R. Taylor (1993). "The environmental benefit of coal gasification using the BGL gasifier." Fuel **72**(3): 305-314.

Corti, A. and L. Lombardi (2004). "Biomass integrated gasification combined cycle with reduced CO₂ emissions: Performance analysis and life cycle assessment (LCA)." Energy **29**(12-15): 2109-2124.

Doctor, R., J. Molburg, et al. (2001b). Life-cycle analysis of a Shell gasification-based multi-product system with CO₂ Recovery. The First National Conference on Carbon Sequestration, Washington DC.

Dowd, R. (2000). Wabash River Coal Gasification Repowering Project Final Technical Report. Morgantown, West Virginia, The U.S. Department of Energy Office of Fossil Energy National Energy Technology Laboratory.

EFMA (2000a). Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry. Booklet No.1: Production of Ammonia. Brussels, European Fertilizer Manufacturers Association.

Elsayed, M. and N. Mortimer (2001). Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates. Final Report: B/U1/00644/00/00, Sheffield Hallam University.

Felder, R. (2004). Ecological impact of the use of methane from wood gasification. Internal report within the Ecogas project. Villigen, Switzerland, Paul Scherrer Institute (PSI).

Goedkoop, M., A. Schryver, et al. (2008). Introduction to LCA with SimaPro 7, PRe Consultants.

Hamelinck, C. N. and A. P. C. Faaij (2002). "Future prospects for production of methanol and hydrogen from biomass." Journal of Power Sources **111**(1): 1-22.

Heller, M. C., G. A. Keoleian, et al. (2003). "Life cycle assessment of a willow bioenergy cropping system." Biomass and Bioenergy **25**(2): 147-165.

Hofbauer, H. (2006). Gas-cleaning at the Gussing plant update. ThermalNet, Lille.

Hofbauer, H., R. Rauch, et al. (a). Hydrogen Rich Gas from Biomass Steam Gasification. Vienna, Institute of Chemical Engineering, Fuel and Environmental Technology.

Hofbauer, H., R. Rauch, et al. (b). Six years experience with the FICFB-Gasification Process. Vienna, Institute of Chemical Engineering.

Hornick, M. and J. McDaniel (2002). Tampa electric polk power station integrated gasification combined cycle project - Final technical report. Morgantown, West Virginia, The U.S. Department of Energy, National Energy Technology Laboratory.

ISO (2006). Environmental management — Life cycle assessment — Principles and framework. Geneva, International Standard Organization BS EN ISO 14040:2006.

Jungbluth, N., F. Dinkel, et al. (2007). Life Cycle Inventories of Bioenergy, Ecoinvent report No. 17. Dubendorf, CH, Swiss Centre for Life Cycle Inventories.

Koroneos, C., A. Dompros, et al. (2008). "Hydrogen production via biomass gasification--A life cycle assessment approach." Chemical Engineering and Processing: Process Intensification **47**(8): 1261-1268.

Ni, M., D. Y. C. Leung, et al. (2006). "An overview of hydrogen production from biomass." Fuel Processing Technology **87**(5): 461-472.

Paisley, M. and R. Overend Verification of the Performance of Future Energy Resources' SilvaGas® Biomass Gasifier - Operating Experience in the Vermont Gasifier, Future Energy Resources Corporation.

Paisley, M. and M. Welch (2003). Biomass gasification combined cycle opportunities using the future energy Silvagas gasifier coupled to Alstom's industrial gas turbines. AMSE Turbo Expo Land, Sea and Air, Georgia World Congress Center.

Palonen, J., T. Anttikoski, et al. (2006). The Foster Wheeler gasification technology for biofuels: refuse-derived fuel (RDF) power generation. PowerGen Europe.

Reinhard, R. (2000). "FICFB." from www.ficfb.at/.

Renzenbrink, W., R. Wischnewski, et al. High temperature Winkler (HTW) coal gasification - A fully developed process for methanol and electricity production.

Richards, M. (1995). Texaco Gasification Process, Innovative Technology Evaluation Report. Cincinnati, Ohio, National Risk Management Research Laboratory, U.S. Environmental Protection Agency.

Shelton, W. and J. Lyons (2000). British Gas / Lurgi Gasifier IGCC Base Cases, EG and G.

SKM (2006). Port Talbot Renewable Energy Plant. Glasgow, Sinclair Knight Merz.

Stahl, K. and M. Neergaard (1998). "IGCC power plant for biomass utilisation, värnamo, Sweden." Biomass and Bioenergy **15**(3): 205-211.

Stahl, K., L. Waldheim, et al. (2004). Biomass IGCC at Varnamo, Sweden - Past and future. GCEP Energy Workshop, Frances C. Arrillaga Alumni Center, Stanford University, California.

Thornley, P., P. Upham, et al. (2009). "Integrated assessment of bioelectricity technology options." Energy Policy **37**(3): 890-903.

Van der Drift, B. Status of biomass gasification, Energy Reseach Centre of the Netherlands.

Williams, R. (1998). Cost-competitive Electricity from Coal with Near-zero Pollutant and CO2 Emissions. Review - Draft. Princeton, PU/CEED.

Zheng, L. and E. Furinsky (2005). "Comparison of Shell, Texaco, BGL and KRW gasifiers as part of IGCC plant computer simulations." Energy Conversion and Management **46**(11-12): 1767-1779.