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Assessing economically viable carbon reductions for the production of ammonia from biomass gasification

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ABSTRACT

Greenhouse gas emissions from fertiliser production are set to increase before stabilising due to the increasing demand to secure sustainable food supplies for a growing global population. However, avoiding the impacts of climate change requires all sectors to decarbonise by a very high level within several decades. Economically viable carbon reductions of substituting natural gas reforming with biomass gasification for ammonia production are assessed using techno-economic and life cycle assessment. Greenhouse gas savings of 65% are achieved for the biomass gasification system and the internal rate of return is 9.8% at base-line biomass feedstock and ammonia prices. Uncertainties in the assumptions have been tested by performing sensitivity analysis, which show, for example with a ±50% change in feedstock price, the rate of return ranges between −0.1% and 18%. It would achieve its target rate of return of 20% at a carbon price of £32/t CO_2, making it cost competitive compared to using biomass for heat or electricity. However, the ability to remain competitive to investors will depend on the volatility of ammonia prices, whereby a significant decrease would require high carbon prices to compensate. Moreover, since no such project has been constructed previously, there is high technology risk associated with capital investment. With limited incentives for industrial intensive energy users to reduce their greenhouse gas emissions, a sensible policy mechanism could target the support of commercial demonstration plants to help ensure this risk barrier is resolved.

1. Introduction

The Copenhagen Accord (UNFCCC, 2010) recognises that to avoid experiencing high levels of climate change, as described by the Intergovernmental Panel on Climate Change (IPCC, 2007), requires greenhouse gas concentration in the atmosphere to stabilise. The scientific evidence surrounding this states that global mean average temperatures should therefore not rise by more than 2 °C (above pre-industrial levels). The European Commission has renewable commitments (2009) and the UK Government (HM Government, 2008) has established carbon budgets and targets out to 2050 to ensure that all sectors decarbonise at a rate that is compatible with avoiding this 2 °C temperature rise.

This study considers the potential use of biomass to reduce greenhouse gas emissions from fertiliser production and in particular ammonia production, as a step change measure to decarbonise the industrial sector. The conventional method to produce N-fertilisers involves the production of ammonia via the Haber–Bosch process (EFMA, 2000a; EFMA, 2000b), which combines H_2 from steam reforming of natural gas and N_2 from air. Steam reforming is very energy intensive, accounting for 1.2% of the global primary energy demand (Kongshaug, 1998) and production alone represents 0.93% of global greenhouse gas emissions (IFA, 2009). Moreover, fertiliser demand has been shown to increase over the coming decades (Tenkorang & Lowenberg-DeBoer, 2008) due to the growing global population striving to secure food and nutrition for all. A further factor to be considered is issues associated with high levels of climate change. Modelling results by the IPCC have shown that global warming above 3 °C was found to have negative impacts global food production (Easterling et al., 2007). This and the issue of population will consequently result in a further increase in global emissions from the production and application of N-fertilisers (Smith et al., 2007).

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There are considerable arguments to suggest that short-term and urgent measures to reduce emissions will have significant benefits in the longer-term (Anderson and Bows, 2008; Macintosh, 2010; Meinshausen et al., 2009). However, the only step-change technologies presently discussed to decarbonise ammonia production and subsequent fertiliser production are the as yet unproven carbon capture and storage technology and H_2 production from renewable electrolysis (IFA, 2009). Only short-term incremental measures, such as 'best available practices' for existing natural gas based fertiliser production are being implemented (IFA, 2009) and these are largely exhausted. Therefore, it is appropriate to examine the feasibility of producing hydrogen for ammonia, which is the most energy intensive step when producing N-fertiliser, from existing resources and more developed technologies. The goal of this study is to assess the viability of achieving economically viable carbon reductions by replacing natural gas steam reforming with H_2 rich syngas from biomass gasification during ammonia production. The study is performed using techno-economic assessment (TEA) and life cycle assessment (LCA) methodologies.

2. Background and rationale

2.1. The benefits of using biomass

Using a low carbon alternative to natural gas during reforming could help reduce the net greenhouse gas emissions burden. However, many renewable energy sources are not amenable to the provision of high temperature heat, for example wind, tidal and wave resources are more amenable to direct conversion to electricity, yet it is key for process plant operations that the fuel is fixed carbon, storable and available continuously. With this in mind, biomass represents a possible low carbon fuel source for the production of ammonia. Biomass also has the advantage of having a high hydrogen to carbon ratio so that it has potential to provide a H_2 rich fuel source, as required by the ammonia synthesis process. However, it is necessary to first convert the biomass to a usable form for ammonia synthesis; in this case by gasification. Experience with biofuels has shown that the conversion route and in particular the land use change assumptions (Whitaker et al., 2010) can have substantial impacts on the overall greenhouse gas savings achieved. Therefore it is essential to carry out a full and comprehensive TEA and carbon accounting of the entire system to ensure that fuel switching will have the desired results.

2.2. The role of techno-economic analysis and carbon accounting

LCAs of the energy use, environmental impacts and land use implications have shown that using biomass to produce ammonia and N-fertiliser from gasification or anaerobic digestion (Ahlgren et al., 2008, 2010; Gilbert and Thornley, 2010) could provide considerable greenhouse gas reductions. The use of synthesis gas from peat to produce ammonia has also been explored (Koljonen and Sodervall, 1991). However, commercial feasibility is reliant on not just the technical and environmental, but also the economic performance of a new technology. The novelty in this study is that it evaluates all of these aspects on a common basis to provide insights into the practicality of actually achieving economically viable carbon reductions via the biomass gasification route – underpinning potentially new exploitation routes for biomass. Furthermore, the findings can then be compared to similar studies that evaluate the cost-effectiveness of other biomass end-uses, for example energy use (Thornley and Gilbert, 2010).

2.3. Methodology

A range of gasification technologies, scales and production routes to produce ammonia from biomass gasification has been preliminarily assessed (Alexander et al., 2010; Gilbert et al., 2009) and this paper outlines a likely process route, and level of biomass required to substitute natural gas during ammonia synthesis. The system operating parameters are summarised as follows. The scale of the ammonia plant is 1200 tpd and it operates at 30 bar for 8280 hpa. The annual production of ammonia is 414,000 tpa.

Mass and energy balances for the system, from gasifier feed to ammonia output, were developed with the aid of ASPEN Plus; a simulation software for the design and operation of chemical processes. This quantifies the energy use and importantly the amount of biomass required and its flow in the system. An LCA approach is used to determine the impacts of all greenhouse gas[1] emissions when producing ammonia from biomass gasification compared to natural gas reforming. The LCA software used is SimaPro. The findings are expressed as global warming potential (GWP) in the form of CO_2eq. GWP defines the relative contribution of the greenhouse gases to global warming over a set time period, in this case 100 years; for CO_2 it is 1 and for CH_4 and N_2O it is assumed to be 25 and 298 respectively. Given the potential range in emissions associated with the variation in the biomass supply chain and the impact of future climate change and renewable related policy, two sensitivity analyses are completed. The first assesses the change in GWP when the greenhouse gas emissions from the production, transportation and gasification of the biomass are altered by ±50%. The second uses a projected LCA (Pehnt, 2006) to assess the impact of decarbonising the energy system, in this case through the UK Government's commitments to an 80% cut in greenhouse gas emissions across all sectors by 2050 (CCC, 2008).

The TEA uses published data to calculate the anticipated capital cost of a "biomass gasification to ammonia" system. This is combined with projected operational costs to calculate the net present value (NPV) of the facility for given ammonia and carbon prices with a discount rate of 10% (Phillips et al., 2007; Swanson et al., 2010). The calculations are carried out in £ as the study is UK focused with biomass imports from Northern Europe. The carbon savings achieved by the facility, calculated using the LCA methodology and a notional value per unit of carbon dioxide saved is assigned to these, constituting additional revenue for the plant. This figure is then varied to determine the carbon price at which the project meets minimum investment criteria which would make it an attractive proposition for project developers.

The functional unit in the study is 1 kg NH_3 produced at the ammonia plant. This was selected due to the size of the ammonia industry and in particular the scale of each production site. Using a functional unit that considered the further upgrade to N-fertiliser would not be as relevant, as the production steps involved in the natural gas and the biomass gasification systems are the same once the biomass-derived ammonia has been produced. Furthermore, assuming any end-use of the fertiliser could be misleading, as the main focus of this paper is the potential to decarbonise the production of ammonia.

When presenting the mass and energy balances, TEA and LCA data in Section 4 there is inevitably a trade-off between presenting all the data (full transparency) and interpreting the data so that it is meaningful for a wider audience (eg policy makers/advisors and industry). Whilst step by step inventory analysis is not included, the key parameters for the technical assessment of the biomass gasification system and the source of inventory data for the natural gas system are included. Furthermore, a large proportion of the data used for the economic analysis is presented in Section 3 and/or

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[1] Within this study the greenhouse gases quantified are CO_2, CH_4, N_2O, HFCs, PFCs, SF_6 – described as the 'basket of six' by the Kyoto Protocol.

literature references are provided for the data used. Where data references have not been presented for the LCA, it should be assumed that the data is taken from EcoInvent v2.2, adjusted for UK conditions at a primary and secondary level. As parts of this analysis are the formulation of an inventory for the biomass gasification system, this is included in Section 4: Results.

3. System definition

3.1. Ammonia production from natural gas steam reforming

The reference system is described in detail by the European Fertilizer Manufacturers Association (EFMA, 2000a). Natural gas is assumed to be piped from the North Sea to the production plant. Reforming converts CH_4 and light hydrocarbons into H_2, CO and CO_2 using steam supplied by additional burning of natural gas. In the secondary reformer, further energy is supplied to increase conversion by internal combustion of natural gas with air. The nitrogen supply in the process air should equal the ammonia nitrogen content plus purge losses. The shift reactor converts CO into CO_2 and H_2 via the water-gas shift reaction and CO_2 is then removed to leave H_2, N_2 and excess process steam in the process gas. Finally, methanation converts trace CO and CO_2, as they are poisonous for the ammonia synthesis catalyst. Ammonia synthesis takes place by the Haber–Bosch process over an iron catalyst at pressures ranging between 100 and 250 bar and at 350–550 °C. The ammonia plant could be self-sustained however small steam export and electrical import is common practice. Life cycle inventory for conventional ammonia production is taken from Ecoinvent v2.2 and is adjusted for UK data (Althaus et al., 2007; EFMA, 2000a). The main inputs are natural gas feedstock and additional natural gas fuel for the primary reformer, at 23.4 MJ/kg NH_3 and 8.1 MJ/kg NH_3 respectively on the basis of lower heating value.

3.2. Ammonia production from biomass gasification

The system boundaries cover the growth, processing and delivery of the biomass to a chipping site, transportation to the gasification/ammonia plant and subsequent production of ammonia. This covers the input of materials from the technosphere and the natural system and subsequent emissions to air, soil and water. The system boundaries are also outlined in Fig. 1.

3.2.1. Biomass growth, processing and delivery

3.2.1.1. Forestry growth. The biomass is procured from the Northern State forests of Poland, which has high lingo-cellulosic biomass production potential (Fischer et al., 2010) and convenient export trade routes. The forest is assumed to be productive over a period that exceeds the operation of the ammonia plant and forestry activities including tree nurseries, tending, thinning, cutting and transportation of the forestry to the nearest forest road (Werner et al., 2007) have been included in the scope of analysis.

The allocation of the forestry by-products between saw logs, roundwood and harvested branchwood is calculated based on a relative price value of 4:2:1 for each of the by-products respectively (Elsayed et al., 2003). Allocation attributes a proportion of the emissions to the small roundwood for the carbon sequestered, land-use, fossil-energy input for felling and emissions, as shown in Fig. 1. Table 1 describes in more detail, the physical properties of the small roundwood used for the solid biomass feedstock.

3.2.1.2. Processing (wood chipping and drying) and delivery. The solid biomass is transported 40 km (round-trip) by a flatbed 32t EURO5 lorry to the wood chipping plant. During transportation and any subsequent transportation, it is assumed that 3% of the biomass is lost per transport step. It is assumed that the degradable organic carbon within the debris, and any subsequent debris, aerobically

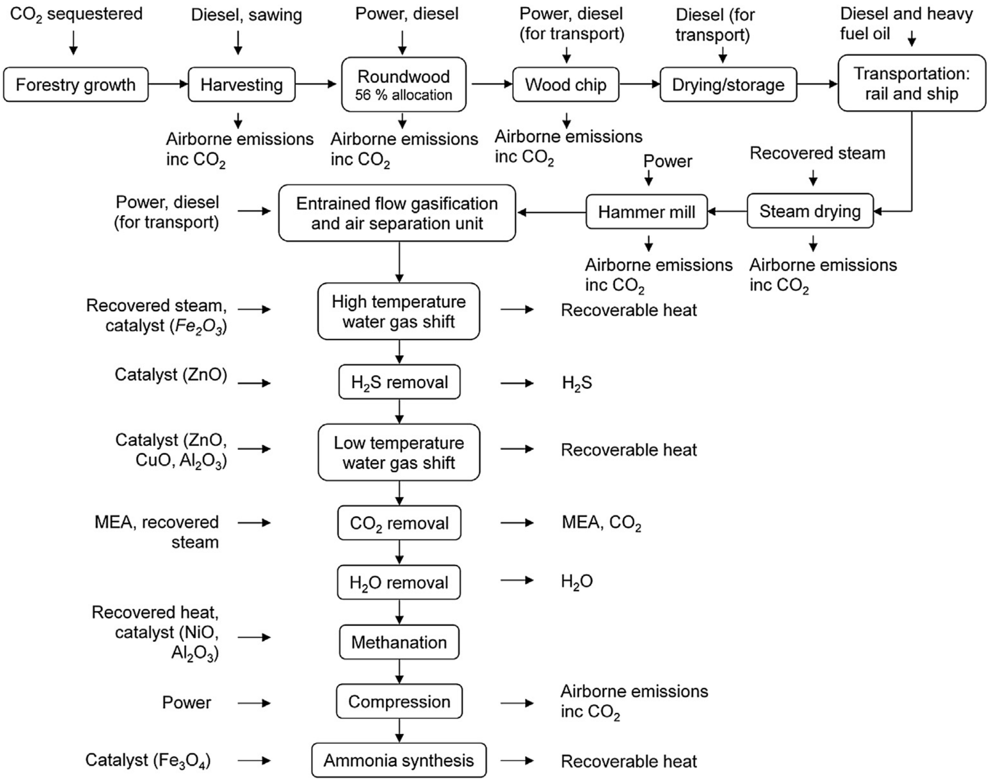

Fig. 1. Schematic of ammonia production for the biomass gasification system.

Table 1
Physical properties of biomass feedstock.

Properties	Value	Units
Higher heating value (dry ash free)	20.21	MJ/kg
Carbon content, dry basis	49.89	%
Bulk density, dry basis	500	kg/m^3
Moisture content, wet basis	50	%

degrades as CO_2 equal to the CO_2 sequestered during growth. At the plant the solid biomass is chipped to a bulk density of 300 kg/m^3, requiring approximately 0.076 kWh$_e$/kg NH_3 (Werner et al., 2007). It is assumed that 5% of the biomass is lost during chipping. The woodchip is then transported a further 40 km by a 32 t EURO5 lorry to the drier and storage area. It is naturally dried from 50% to 35% moisture content (MC) over a 3 month period (Gigler et al., 1999). The woodchip is transported 170 km by freight train to the port of Gdansk, Poland and loaded on to a dry bulk vessel. It is then shipped 1350 km (Searates, 2010) to the port of Felixstowe, England where it is stored. We have assumed that the lorry is empty for the return leg. The shipping is assumed to be a chartered vessel and the train is assumed to be one way. The assumptions for greenhouse gas emissions are taken from Ecoinvent v2.2.

3.2.2. *Biomass gasification*

3.2.2.1. Drying and milling. From storage, the woodchip is sent to a superheated steam dryer (SSD) and dried to approximately 12% MC (wet basis). The dried material is then passed to a hammer-mill, which reduces the particle size to <2 mm before being transported to the gasifier (van Swaaij et al., 1994).

3.2.2.2. Entrained flow gasification. The gasification technology selected is pressurised entrained flow gasification operating on O_2-enriched air. The technology is based on the Shell Coal Gasification Process (SCGP), which is a dry-fed pressurised process operating at 1200–1600 °C and 30–40 bar (Eurlings and Ploeg, 1999). Conventional operation is with pulverised coal and 95% purity O_2 from a dedicated air separation unit (ASU), with heat removal to maintain the required temperature. However, in the present case the gasifier is supplied with O_2-enriched air ($\sim$55 wt% O_2). For the purposes of this study the level of O_2 enrichment is selected to maintain a gasification temperature of 1200 °C while at the same time providing the correct amount of N_2 for ammonia synthesis. The actual required temperature will be a function of the ash slagging characteristics of the feedstock, and may be higher. It is acknowledged that such operation may require design modification, notably to the heat removal arrangement.

Entrained flow gasification involves some additional costs compared to other systems because of the level of feedstock pretreatment required. However, Alexander et al. (2010) has shown it to be a suitable technology choice for ammonia synthesis because of scalability; little or no tar and methane content and; the use of pressurised gasification to reduce compressor loading prior to ammonia synthesis. The gasifier has been modelled using a simple equilibrium assumption based on Gibbs free energy minimisation (Doherty et al., 2009; Robinson and Luyben, 2008).

The gasifier is assumed to operate adiabatically; therefore the only heat energy requirement within this system is the steam input for the SSD, which is 0.51 kWh/kg syngas. This steam is provided by heat recovery during syngas conditioning. The process is exothermic and is able to meet the SSD demand and still export a surplus of steam and hot water.

During gasification imported electrical power is required for hammer milling and for air separation. Electrical power is then required for compression of the product gas prior to ammonia synthesis and for the water used for specific heat recovery stages. The total electricity requirement for the system is 0.37 kWh/kg NH_3. The electrical power supply is based on the UK's 2010 electricity mix (adjusted in SimaPro).

3.2.3. *Syngas conditioning and ammonia synthesis*

The syngas conditioning process is adapted from the conventional ammonia production system for natural gas. As there is no methane or higher hydrocarbons, the reforming stages are not required. The demand for added steam at the high temperature water gas shift (HTWGS) is reduced due to the presence of significant amounts in the syngas. All operational parameters are available in literature (EFMA, 2000a; Harding, 1959; Slack, 1973).

4. Results

4.1. *Mass and energy balance for ammonia production from biomass gasification*

Ammonia production using biomass gasification is modelled as a single integrated process. The key mass and energy inputs and outputs of the biomass gasification system are given in Tables 2 and 3. Since 1 kg syngas is produced from 0.72 kg of biomass (35% MC), it can be estimated that for 1 kg ammonia approximately 2.71 kg biomass (35% MC) is required (not including additional biomass losses in the system). It should be assumed that the surplus heat in Table 3 results in less biomass being required within the system.

4.2. *Techno-economic assessment over the system life cycle*

The economic data used is derived from relevant literature sources. Where multiple sources were available, cost averages have been calculated. Data is corrected for scale using a scale factor of 0.65. For large-scale chemical plants, the scaling factor is normally between 0.6 and 0.7, with 0.65 being a common figure. In terms of biomass applications, Boerrigter (2006) states that a scaling factor between 0.6 and 0.7 is suitable for moderate to large conversion plants. All data is adjusted to 2009 (January) UK £ prices using either plant cost index US CECPI (1957–1959 = 100) or a relevant

Table 2
Biomass gasification system mass balance, expressed as kg/kg NH_3.

Drying	
Input	
Biomass (35% MC)	2.71
Steam (SSD)	0.72
Output	
Biomass (12% MC)	2.00
Residual steam/water	1.43
Gasification	
Input	
Biomass (12% MC)	2.00
Enriched air	1.76
O_2	0.97
Output	
Syngas	3.74
Ash	<0.38 (0.02)
Ammonia synthesis	
Input	
Syngas	3.74
Steam	1.90
MEA make-up	0.02
Output	
H_2S	<0.01
Waste water	0.70
Unreacted products	0.07
CO_2	3.16

Table 3
Biomass gasification system energy balance.

Heat requirements	Temperature (°C)	MWh/kg NH_3
Steam for HTWGS	250	0.001
Heat for Methanator	300	0.0002
MEA Regeneration	120	0.0027
Heat Produced		
Heat recovery (high pressure steam)	251	0.0018
Heat recovery (low pressure steam)	125 (310)	0.0046
Heat recovery (water)	57–91	0.0001
Water removal reactor	40	<0.0001

rate of inflation. An exchange rate exchange rate of USD$1 = £0.64 is used (Antweiler, 2009).

4.2.1. *Capital costs*

The capital costs shown in Table 4 are separated into six sections: feedstock preparation, air separation, gasification, ammonia synthesis, indirect costs (legal, engineering, construction and contingency costs) and land. The data represents a Total Plant Cost, which includes equipment, materials, installation and any contingencies.

Drying and milling costs are calculated using data from Wardrop Engineering Inc. (1990) cited by Amos (1998) and Thek and Obernberger (2004). Air separation and gasification costs are derived from Swanson et al. (2010) and Williamson and McCurdy (2009) and include subsequent compression stages required for gasification. The costs used for gasification are for a slurry-fed entrained flow biomass gasifier and a slagging entrained flow biomass gasifier with mass feed rates of 2000 tpd, which have been scaled accordingly.

Ammonia synthesis costs are calculated using data for a natural gas ammonia production plant (Crawford et al., 2007). The costs used are for a 1500 tpd ammonia production plant, operating pressure not stated. Additional cost information is taken from Andersson et al. (2006), Singh et al. (2003) and Phillips et al. (2007). As shown in Table 4 this is the largest cost, due to the number of process stages required for ammonia production. Indirect costs are also from Crawford et al. (2007), Spath et al. (2005) and Villanueva Perales et al. (2011). Finally, land costs are taken from Swanson et al. (2010) and Villanueva Perales et al. (2011).

4.2.2. *Operating costs*

The operating costs shown in Table 5 are divided into six sections: basic labour, maintenance, general overhead (inc. salary benefits), materials, indirect and feedstock logistics.

Labour costs are calculated using data from Phillips et al. (2007). It is assumed that a workforce of 54 people are required. Additional salary benefits are included in the general overhead. Maintenance (including both labour and materials) is assumed to be 2.3% of the capital costs (Bridgwater et al., 2002; Phillips et al., 2007; Villanueva Perales et al., 2011; Huisman et al., 2011).

Table 4
Capital Costs for the biomass gasification system in 2009.

Process	Cost (x £1000)
Feedstock preparation	9892
- Storage & handling	1194
- Drying	8039
- Milling	660
Air separation (& compression)	21,552
Gasification	48,036
Ammonia synthesis	52,027
Indirect Costs	37,680
Land	5523
Total	174,712

Table 5
Operating Costs for the biomass gasification system in 2009.

Area	Annual cost (x £1000)
Basic labour	1582
Maintenance (Labour & Materials)	3878
General Overhead	1503
Materials	48,095
- Biomass feedstock	29,130
- Catalysts & chemicals	3949
- Water (Process & Cooling)	798
- Electricity (Process & Overhead)(@ 8.31 p/kWh)	13,944
- Waste disposal	274
Indirect (Fixed Costs)	3447
Feedstock logistics	15,550
- Road	5950
- Rail	7523
- Sea	2077
Total	74,055

Materials data is collected from Crawford et al. (2007), Singh et al. (2003), DECC (2011), Phillips et al. (2007), and Sinnott (2005). The materials include biomass feedstock, relevant catalysts and chemicals, process and cooling water, process and overhead electricity and waste disposal. The price of the biomass feedstock is £40/odt (oven dried tonne) (Bridgwater, 2009), which accounts for 39.3% of the overall operating costs. Electricity for both process and overheads cost 8.31 p/kWh (DECC, 2011), whilst process and cooling water are priced at 60 p/t and 1.5 p/t respectively (Sinnott, 2005). Waste disposal covers both solid and water waste. Indirect (fixed) costs cover legal and administrations fees payable during operation (Crawford et al., 2007).

The majority of transport cost data are derived from Hamelinck et al. (2005). Taking into account fuel costs, cargo capacity and chartering vessels, the feedstock logistics represents 21% of total operating costs.

4.2.3. *Economic viability*

Given that the biomass derived ammonia will be competing mainly with imported fossil fuel based ammonia, it is necessary to assess whether the system will be economically attractive when providing ammonia at a competitive price. For a novel biomass-based process a target rate of return of 20% (real basis) is assumed in order to assess the financial viability of such a project. This target is not unreasonable for a novel process since typical targets for established processes range from 6% to 15% (Meier and Tarhan, 2006; Tucker, 2009). The economic assumptions for this assessment are as follows. The economic life of the plant is assumed to be 20 years, operating for 8280 hpa. It is also assumed that the capital distribution between years 0 and 1 is 50%.

Three prices for ammonia are taken for the period 2000–2009, converted from USD$ to 2009 £: the 10 year average (£233.01), the 2000–2004 average (£146.62) and the 2005–2009 average (£319.39) (US Department of Agriculture, 2010). Using this data, the internal rate of return (IRR) for each price scenario is calculated based on an annual ammonia production of 414,000 tpa, which equates to 1200 tpd operating at 8280 hpa. The rates of return are based on a plant life of 20 years and 2 years of construction and the results are shown in Table 6.

Table 6 shows that the price of ammonia fluctuates with market prices, which changes the rate of return. The overall 2000–2009 average price delivers an internal rate of return of 9.8%, which is caused by low ammonia prices during 2000–2004. However the target internal rate of return is met comfortably at 27.1% during the 2005–2009, which states that the biomass derived ammonia plant is economically viable with regards to more recent ammonia prices.

Table 6
Internal Rates of Return based on 2000–2009 ammonia prices.

Point	Ammonia price (£/t)	Internal rate of return (%)
2000–2004 average	146.62	n/a
2000–2009 average	233.01	9.8
2005–2009 average	319.39	27.1
Target rate of return (20%)	281.14	20

Table 7
Internal Rates of Return based on 2000–2009 ammonia prices (±10% Capital Cost).

Point	Ammonia price (£/t)	Internal rate of return (%)	Internal rate of return (−10% C.C) (%)	Internal rate of return (+10% C.C) (%)
2000–2004 average	146.62	n/a	n/a	n/a
2000–2009 average	233.01	9.8	12.3	8.6
2005–2009 average	319.39	27.1	30.8	24.8
Target rate of return	281.14	20	23.2	18.2

4.3. *Carbon accounting over the system life cycle*

For the inventory analysis, the forestry growth attributed to the biomass gasification system is assumed equal to the sum of biogenic CO_2 removed during ammonia production and aerobic degradation of losses in the system. In the biomass gasification system, the main sources of carbon emissions are the fossil based power supply for the gasification and ammonia plant. Fig. 2 shows the GWP impact analysis for both systems, divided into key process steps. The total GWP for the natural gas steam reforming system is estimated to be 1.93 kg CO_2eq/kg NH_3 and for biomass gasification system it is estimated to be 0.67 kg CO_2eq/kg NH_3. Therefore the carbon dioxide saving is approximately 1.26 kg CO_2eq/kg NH_3 or a saving of 65%.

4.4. *Sensitivity analysis*

4.4.1. *Sensitivity to capital costs and feedstock price*

Two sensitivity analyses are completed to assess the effect of fluctuations in capital cost and feedstock price on the rates of return. The capital cost shown in Table 7 is varied by ±10% to allow for discrepancies in the cost data used and the impacts on economic viability.

The price of European sourced woody biomass varies by location from €10–20 (~£9–18) to €160 (~£142), with a mean of €70 (~£62) (£1 = €1.12 (Central European Bank, 2011)). However, it is unlikely that biomass conversion systems would operate using high cost feeds (Bridgwater et al., 2002) and so a lower price of £40/t was used for the base analysis carried out here. However, sensitivity to a large price range should be examined to reflect possible variations and so the feedstock price was varied by ±50%, as shown in Table 8.

4.4.2. *Sensitivity to upstream processes and future climate policy*

Two sensitivity analyses are completed on the LCA. The first sensitivity assesses the effect of variations in the greenhouse gas emissions associated with the production, transportation and gasification of the biomass. The GWP for these steps are varied by ±50% to observe the impact in potential changes in growing conditions (land-use change, feedstock type, agricultural processes), biomass location, feedstock preparation and gasification operating conditions. In Fig. 2 these steps produce 0.37 kg CO_2eq/kg NH_3 (0.67 kg CO_2eq/kg NH_3 in total). Applying the sensitivity analysis, the total GWP ranges between 0.5 (−50%) and 0.88 (+50%) kg CO_2eq/kg NH_3.

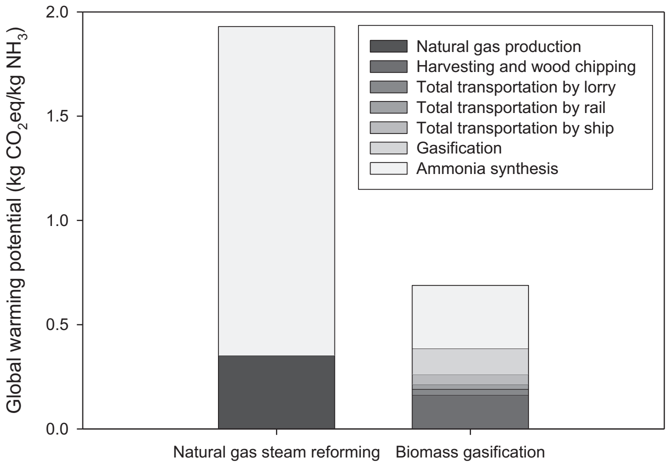

Fig. 2. Global warming potential for natural gas steam reforming and biomass gasification systems.

The second sensitivity uses a projected LCA to assess the effect that the future decarbonisation of the energy and transport sector could have on the production of ammonia for both systems. Examining Fig. 2, with net biogenic emissions assumed to be zero, the direct and indirect sources account for the entire GWP in the biomass gasification system. This can be split into the consumption of transport fuels, power demand (chipping, gasification and ammonia synthesis) and direct fossil fuel combustion (harvesting, catalyst production and plant production). Taking the Committee on Climate Change's possible UK path to an 80% reduction (CCC, 2008) and acknowledging that international shipping emissions and non-CO_2 gases in agriculture are not included, Fig. 3 shows the projected GWP for both systems in2050.[2]

5. Discussion

5.1. *Techno-economic*

The calculated capital cost (Total Plant Cost) for a 1200 tpd ammonia production plant based on biomass gasification is £174.7 M. This compares reasonably with a study for a plant based on steam reforming of natural gas, which gives a capital cost after adjustment for scale and time of £165.4 M (Bartels and Pate, 2008). Although there is considerable scope for variation in such estimates, it could be argued that the biomass route does not require the steam reforming process, but entails additional costs for feedstock preparation resulting in a higher overall capital cost. The same study gives a capital cost of £330.7 M for a plant based on coal gasification – significantly higher and attributable amongst other things to the need for a much larger air separation plant and more demanding gas clean-up.

The cost of production of ammonia for both natural gas and biomass gasification systems is heavily influenced by the price of the feedstock, as well as by process scale. Bartels and Pate (2008) give US$498/t (approximately £250/t) for an 1800 tpd natural gas based plant and US$367/t (approximately £184/t) for an 1800 tpd coal based plant, both in 2007 and using the feedstock price at the time. Allowing for the scale difference, the proposed plant (at £247/t) could be seen as more expensive than the coal plant but possibly less expensive the natural gas plant. However, fluctuations in feedstock price render such conclusions dangerous – for example

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[2] Assumes that neither system uses CCS to store direct CO_2 emissions from ammonia synthesis.

Table 8
Internal Rates of Return based on 2000–2009 ammonia prices (±50% Feed Cost).

Point	Ammonia price (£/t)	Internal rate of return (%)	Internal rate of return (−50% feed cost) (%)	Internal rate of return (+50% feed cost) (%)
2000–2004 average	146.62	n/a	n/a	n/a
2000–2009 average	233.01	9.8	18	−0.1
2005–2009 average	319.39	27.1	34.2	21.3
Target rate of return	281.14	20	27.4	13.3

the price of natural gas varied between \$0.14 (£0.09)/1000 L and \$0.31 (£0.17)/1000 L between 2005 and 2009 (US Energy Information Administration, 2011).

5.1.1. Economic sensitivity

Reducing the capital cost results in an increase in IRR and vice versa. The sensitivity varies depending on the ammonia price. At the "target rate of return" ammonia price, a +10% change in capital cost gives a −9% change in IRR, and a −10% change in capital cost gives a +16% change in IRR. These are substantial impacts, illustrating the risk associated with large capital investments in novel technologies, where the risk of cost over-runs would generally be considered higher than for conventional plants.

Assessing the sensitivity to feedstock price, it varies depending on the ammonia price. At the target rate of return ammonia price, a +50% change in feedstock price gives a −33.5% change in IRR, and a −50% change in feedstock price gives a +37% change in IRR. Therefore, feedstock price has the potential to greatly influence the economic viability of a project. This highlights the need to guarantee long-term feedstock contracts at a fixed price where possible.

5.2. Carbon accounting

With a saving of 1.26 kg CO_2eq/kg NH_3 (i.e. a 65% reduction compared to the natural gas equivalent) the biomass gasification system delivers substantial mitigation of the GWP. This is consistent with other studies that found gasification (Ahlgren et al., 2008) and anaerobic digestion (Ahlgren et al., 2010) could substantially reduce the GWP of ammonium nitrate fertiliser (the functional unit differs, but ammonia is the most energy intensive step for the production of a range of N-fertilisers including urea, ammonium nitrate and ammonium sulphate).

Section 4.4.2 shows that even if the emissions associated with biomass production, transportation and gasification are increased by 50% then the GWP savings compared to the natural gas system is still 54%, which far exceeds what could be achieved with available best practices. Given that the main source of emissions for the natural gas system is from steam reforming natural gas feedstock and subsequent CO_2 removal (1.58 kg CO_2eq/kg NH_3), these emissions are now being replaced by biogenic CO_2 in the biomass gasification system. As long as this has been relatively recently fixed compared to its longevity in the atmosphere, considerable variations in upstream biomass processing could be tolerated before the process route is not viable from a carbon perspective.

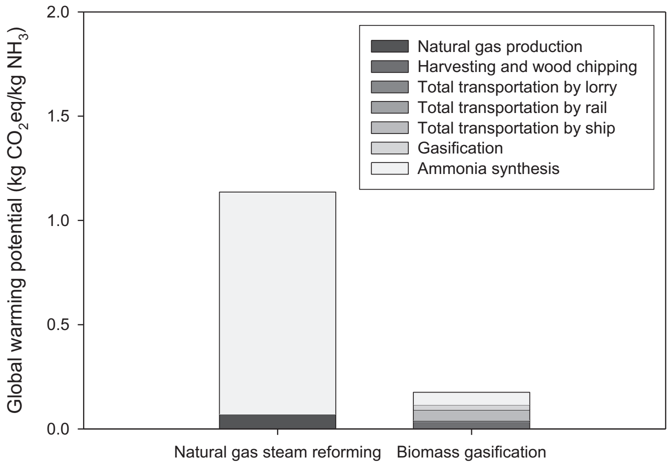

Fig. 3. Projected global warming potential for natural gas steam reforming and biomass gasification systems (2050, 80% reduction in greenhouse gas emissions).

Of course, investments made in strategic plants now should continue to deliver carbon reductions in the long-term and in some cases concerns have been raised that overall decarbonisation trends are such that the actual savings achieved by some new technologies may decrease in future to the extent that the new facility ceases to become "low carbon" in a future "low carbon" context. Assuming that the UK meets its 2050 decarbonisation targets, approximately 75% savings can be made for the biomass gasification system, as shown in Fig. 3. However, only a 41% emissions reduction is achievable for the natural gas system. With its reliance on the transport sector to deliver the imported biomass and high electricity usage during gasification and ammonia synthesis, the results indicate that there is more future potential to decarbonise the biomass gasification system. There are less available avenues for the natural gas system, as most of the CO_2 emissions are directly released during ammonia synthesis from natural gas feedstock conversion to H_2.

5.3. Combining economics and carbon savings

5.3.1. Comparing economically viable carbon reductions

Often achieving carbon savings via new technologies requires additional payments or support compared to conventional fossil-fuel based technologies. In such cases it can make sense to consider the price that must be ascribed to the carbon savings in order to make the new, low-carbon technology competitive with the established fossil fuel alternative. For example, previous work (Thornley and Gilbert, 2010) has shown that biomass district heating systems can be viable at a carbon price of £25/t CO_2 and biomass to electricity at £42/t CO_2. Carrying out a similar evaluation for the ammonia production process described here shows that the plant would achieve its target rate of return of 20% with the ammonia price of the average of 2000–2009 at a carbon valuation of £32/t CO_2. This is between the equivalent results for biomass district heating and biomass electricity, showing that ammonia production can achieve carbon reductions at a comparable cost. However, it must be acknowledged that there is a substantial risk involved with investing in such technology and that the price of ammonia is very volatile. If this assessment is repeated with the lower ammonia price of £146.62/t, which was the average for 2000–2004 then a carbon price of £100/t CO_2 is required in order to reach the target IRR of 20%, which is much higher than the heating or electricity assessments. It should also be noted that, at these low ammonia and high carbon prices the annual plant revenue from carbon savings constitutes 46% of its total revenue. Therefore, while ammonia production from biomass may be a potentially cost-effective method of reducing carbon emissions using biomass, plant viability is dependent on high carbon prices during periods of low ammonia prices, which is a substantial and unfamiliar project risk for developers. This is likely to impede investment in the absence of a minimum value and assured longevity of payments for carbon reductions.

5.3.2. Economic barriers and risk

The main economic barriers to implementation of this technology therefore appear to be the existence of currently adequate production plants to supply market needs, the high technology risk involved and the need for high carbon prices to support plant income at times of low ammonia prices. However, it is likely that in a lowly priced ammonia market, there is increased likelihood that carbon prices would also be low – exasperating the desirability. It has already been mentioned above that future global demand for fertiliser is expected to increase in the long-term and so it is likely that new capacity will be required, though not necessarily imminently. It is unlikely that there would be substantial investment in new plants until fertiliser demand recovers from the downturn seen at the end of 2008, during the global recession (VM Group, 2010). Additionally, the ammonia from biomass technology is essentially unproven and therefore high risk. Uncertainty related to new technology, reliability and performance is a substantial barrier to uptake of efficiency improvements in the process industries (Walsh and Thornley, 2012). Of particular importance here is likely to be the potential for variations or impurities in the syngas to lead to deteriorations in ammonia synthesis performance or final ammonia product quality. These risks could likely be minimised by additional cleaning/purification steps prior to synthesis, but this could have significant capital cost and efficiency implications. However, since there is very little difference between the capital expenditure for the biomass and conventional options, it seems unlikely that a significant subsidy for capital expenditure would have a substantial impact on technology viability or the likelihood of implementation.

The fact that very high carbon prices are required to maintain viability at times of low ammonia prices also illustrates the vulnerability of such a project to external market forces and, in the absence of some increased market certainty (either for carbon or ammonia) it seems unlikely that investors would commit to a project, which only offers attractive rates of return when ammonia or carbon prices are much higher than their historical levels and incorporates an unproven technology. Nevertheless it is important to realise that when the ammonia price is at an adequate level this technology offers a highly cost effective option for achieving carbon reductions from biomass.

5.3.3. Impact of carbon price

Table 9 shows the rate of return that is achieved when the project is credited with income for each unit of carbon saved below the fossil fuel reference system at the average 2000–2009 ammonia price. If no carbon credits are applied the internal rate of return is 11%, as in Table 9. The UK Government has recently proposed introducing a carbon floor price for carbon trading of initially £16/t CO_2 in 2013, reaching £30/t CO_2 by 2020. These carbon values would raise the IRR on this project from 10% to 16% and then 20%. Therefore, the envisaged carbon floor price by 2020 would be sufficient for an ammonia plant based on biomass gasification to reach a target rate of return of 20% with 2000–2009 average ammonia prices. However, it should also be noted that much of the production and demand increase for fertiliser products is anticipated in less politically stable regions of the world (VM Group, 2010), which may affect future market price developments and stability. One form of policy support that could make a useful contribution here is reduction of the technology and cost risk of the capital investment, most likely by a supported, large-scale, commercial demonstration plant.

Table 9
Rate of return achieved for different carbon prices at average 2000–2009 prices.

Carbon price (£/tC)	Internal rate of return (%)
0	11
16	16
20	17
30	20
50	25
100	36
200	52

5.3.4. Impact of scale

Biomass could play a key role in providing a reliable, secure method of decarbonising fertiliser production. However, ammonia plants are generally large-scale facilities that would require substantial amounts of biomass. For example, the 414,000 tpa ammonia plant considered here, requires 1,121,000 tpa of biomass feedstock, more than the world's largest biomass power plant. While large-scale co-firing operations, such as those in the UK, have shown that the logistics of facilities of a similar magnitude can be managed, caution would be required with regard to the sustainable sourcing of the feedstock and reliability of supply. Nonetheless, it is important to remember that as the impact of climate change is experienced globally, the importance of maximising low carbon food production will increase and with this, ensuring land productivity will become essential (Roeder et al., 2011), often entailing increased levels of fertiliser consumption. This would suggest that targeting of biomass to the fertiliser sector is, in fact, a very sensible proposition, which would assist decarbonising the sectors that contribute to the emissions floor.

6. Conclusions

Producing ammonia from biomass gasification is economically viable at current biomass feedstock and ammonia prices and can deliver greenhouse gas reductions of 65% compared to conventional ammonia production from natural gas. Furthermore the GWP of ammonia from biomass gasification could reduce further in future, as the energy sector decarbonises. Using the 2000–2009 average ammonia prices, the plant would achieve a target rate of return of 20% at a carbon price of £32/t CO_2, which is competitive with using biomass for electricity or heat. However, the technology is highly sensitive to ammonia prices and if long-term ammonia prices drop then the technology would become reliant on high carbon prices to ensure it remains competitive to investors. Consequently augmenting commodity market price risks to include risks associated with a newly established carbon market is not going to attract investors without additional support. Furthermore, the capital costs have high uncertainty attached to them, resulting in a potentially very high risk investment. A sensible policy support option would be a targeted support of large-scale, commercial demonstration plants to reduce the risk involved with capital investment in the technology.

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