Green nitrogen - possibilities for production of mineral nitrogen fertilisers based on renewable resources in Sweden

Serina Ahlgren
Andras Baky
Sven Bernesson
Åke Nordberg
Olle Norén
Per-Anders Hansson

Institutionen för energi och teknik
Department of Energy and Technology
Swedish University of Agricultural Sciences

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SLU, Sveriges lantbruksuniversitet
Fakulteten för naturresurser och lantbruksvetenskap
Institutionen för energi och teknik

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ABSTRACT

The production of mineral nitrogen is one of the largest fossil energy inputs in Swedish agriculture. However, mineral nitrogen can be produced based on renewable energy. This would lower the dependency on fossil energy in food production.

This project investigated the possibilities and the consequences for the Swedish agricultural sector of producing nitrogen from renewable resources and agricultural raw materials. More specifically, it studied the land use, energy use and greenhouse gas emissions from the production of ammonium nitrate based on wind power, biomass-based combined heat and power (CHP) and thermochemical gasification of biomass. Ammonium nitrate was chosen since it is the most commonly used nitrogen fertiliser in Sweden. The study also compared small-scale and large-scale production and estimated the production costs.

The construction of new plants and integration within existing biomass heat and power production were compared. For many of the scenarios studied, all the technology needed is already available on a commercial basis and production is a matter of combining the different stages.

The production costs based on small-scale wind power were an estimated 43 SEK/kg N. The costs for large-scale production based on biomass combustion were an estimated 8 SEK/kg N, which is very competitive compared with the fossil-based alternatives on the market today. However, the cost estimations were very rough and associated with large uncertainties. More detailed economic modelling and calculations are needed to support any future investment decisions.

The greenhouse gas modelling was performed using life cycle assessment methodology. The results showed that in most of the scenarios studied, greenhouse gas emissions and use of fossil energy can be significantly lowered. The exception was integration of nitrogen production into existing biomass-fired heat and power production, since the reduced electricity output was assumed to be compensated for by marginal coal power.

Using green nitrogen in crop production can substantially lower the energy and carbon footprint of crops. Using these crops for production of biofuels can also lower the carbon footprint of the biofuels, making the comparison to fossil fuels more favourable for biofuels.

In conclusion, greenhouse gas emissions and fossil energy use can be lowered and there seem to be no technological or economic obstacles to producing green nitrogen. Therefore supplying green nitrogen to agriculture should be a high-priority activity, as nitrogen is one of the pillars for food and bioenergy security of supply. However, it is very difficult to make general recommendations on choice of technology and raw materials, since this choice is dependent on the context. Therefore each case much be carefully investigated and the raw material checked for its sustainability.

SAMMANFATTNING

Tillverkning av mineralkväve är en av de största insatserna av fossil energi i det svenska jordbruket. Mineralkväve kan dock produceras baserad på förnybar energi, vilket innebär att beroendet av fossil energi i livsmedelsproduktionen kan minska.

Syftet med detta projekt var att undersöka möjligheterna och konsekvenserna för den svenska jordbrukssektorn om kväve producerades från förnybara resurser. Mer specifikt var syftet att studera markanvändning, energianvändning och utsläpp av växthusgaser från produktionen av ammoniumnitrat baserad på vindkraft, biomassabaserad kraftvärme och termokemisk förgasning av biomassa. Ammoniumnitrat valdes eftersom det är det vanligaste enkla kvävegödselmedlet i Sverige. Syftet var också att jämföra småskalig och storskalig produktion och att uppskatta produktionskostnader.

Både nybyggda anläggningar och integration inom befintlig biomassabaserad kraftvärme har studerats. För många av de studerade systemen finns alla de teknikdelar som behövs redan i kommersiell skala, det är en fråga om att sätta ihop bitarna.

Kostnaden för produktion baserad på småskalig vindkraft beräknades till 43 kr/kg N. Kostnaden för storskalig produktion baserad på förbränning av biomassa beräknades till 8 kr/kg N vilket är mycket konkurrenskraftigt jämfört med fossila alternativ på marknaden idag. Kostnadsuppskattningarna är dock mycket grova och försedda med stora osäkerheter. Mer detaljerad ekonomisk modellering och beräkningar behövs för att stödja eventuella investeringsbeslut.

Modellering av växthusgasutsläpp gjordes med livscykelanalysmetodik. Resultaten visade en minskning av växthusgaser och användning av fossil energi. Undantaget var integrationen av kväveproduktionen i befintligt kraftvärmeverk, eftersom den minskade elproduktionen antogs kompenseras med kolkraft.

Att använda grönt kväve i växtodling kan minska energiåtgången och växthusgasutsläppen markant. Om grödorna används för att producera biodrivmedel kan dessutom klimatavtrycket för biodrivmedlen också minska, vilket ytterligare ökar reduktionen av växthusgaser jämfört med fossila drivmedel.

Sammanfattningsvis kan sägas att växthusemissionerna och fossilenergianvändningen kan sänkas och det verkar inte finnas några tekniska eller ekonomiska hinder för att börja producera grönt kväve. Vi hävdar att grönt kväve till jordbruket bör vara en prioriterad aktivitet eftersom kväve är en av grundpelarna för en trygg försörjning av mat och bioenergi.

Det är dock svårt att ge generella rekommendationer om val av teknik och råvaror till produktion av grönt kväve, eftersom det till stor del är beroende på sammanhanget. Varje fall måste mycket noggrant undersökas och råvaror bör vara hållbart producerade.

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The authors

Contents

1 INTRODUCTION

Nitrogen fertilisers are needed in agriculture to obtain high yields of agricultural crops. Large-scale use of mineral* nitrogen fertilisers began after Second World War and without this, the expansion of the world population would have been impossible (Smil, 2001).

Nitrogen gas accounts for 78% of the volume of our atmosphere. However, converting it to a form that is useful for agriculture costs energy. At present, the production of nitrogen fertiliser accounts for 1.2% of global primary energy demand (IFA, 2009a). Production is most commonly based on natural gas, but gasification of coal and heavy oil also occurs.

In other words, the production of mineral nitrogen fertilisers is based on fossil fuel resources. In the long run, this is not a sustainable solution as the fossil fuels will run out sooner or later. The use of fossil fuels also contributes to global warming, which is believed by many to be the largest threat to mankind. In this report, alternative ways of producing mineral nitrogen fertilisers are investigated.

1.1 Energy use in Swedish agriculture

At present, the total use of energy in Swedish agriculture is estimated to be 9.2 TWh (33 PJ) per year (Figure 1). The energy use can be divided into two parts, direct and indirect. The direct energy is the energy used on farms, while the indirect energy is the energy used for producing purchased inputs, although not including the production of machinery and buildings.

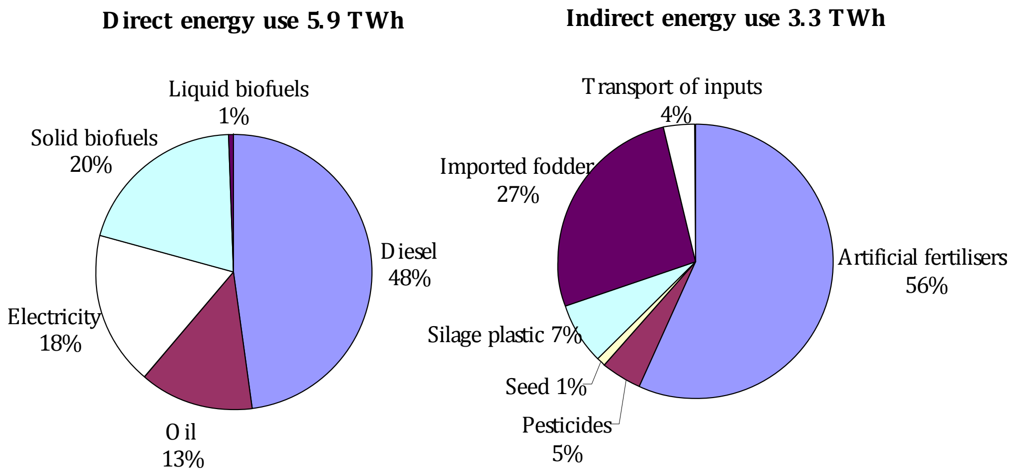

Figure 1. Direct and indirect use of energy in Swedish agriculture (Ahlgren, 2009).

The largest direct energy use is the use of fossil diesel (primarily for tractor fuel). Fossil oil and solid biofuels (mainly wood products and straw) are used for heating animal houses and drying grain (SCB, 2008). Electricity is primarily used in animal production. The Swedish electricity production mix consists mainly of hydro and nuclear power and only 7% is based on fossil energy.

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* The term “mineral nitrogen” is here used to describe industrially produced nitrogen, differentiated from “organic nitrogen” which is present in for example soil organic matter, crop residues and manures. Organic nitrogen can be mineralised by microbes to plant available forms (ammonium and nitrate) but in this study we only study the mineral nitrogen produced by industrial processes.

The largest indirect energy use is the production of fertilisers. The energy used for fertiliser production is largely due to production of nitrogen fertilisers, the main energy carrier being natural gas. The energy consumption for nitrogen production was assumed here to be 39 MJ (11 kWh) per kg N, which is an average European figure based on Jenssen and Kongshaug (2003). To a large extent the other indirect energy inputs are also based on fossil resources, for example silage plastic and the production of imported fodder.

1.2 Greenhouse gas emissions from Swedish agriculture

According to the Swedish national inventory report (Naturvårdsverket, 2009), greenhouse gas (GHG) emissions from Swedish agriculture amounted to 8.43 million metric tonnes (ton) CO_2-equivalents during 2007, corresponding to 13% of national greenhouse gas emissions. This is mainly from animal production (methane) and soil emissions (nitrous oxide). However, that figure does not include the production of inputs such as diesel, fertilisers and imported fodder, nor carbon dioxide release from organic soils.

In a study by Engström et al. (2007), the emissions of GHG from the entire food chain, including the food industry, exports and imports, was calculated to be about 14 million ton CO_2-equivalents. In another study, conducted by the Swedish Board of Agriculture (SJV, 2008a), the GHG emissions from agriculture were estimated to be 15 million ton CO_2-equivalents per year, the largest contribution coming from nitrous oxide emissions from soil (Table 1). However, that report points out the large uncertainties in these quantifications, especially for the nitrous oxide emissions from soil and the carbon dioxide emissions from managed organic soils.

Table 1. Distribution of greenhouse gas emissions from Swedish agriculture (SJV, 2008a)

Activity	% of total
Nitrous oxide from nitrogen in soil	30%
Carbon dioxide from managed organic soils	25%
Methane from animal digestion	20%
Production of mineral fertilisers	10%
Methane and nitrous oxide from manure (storage and spreading)	7%
Carbon dioxide from fossil fuels	7%
Imported feed	3%

As can be seen in Table 1, the production of fertilisers accounts for only 10% of the GHG emissions from agriculture. However, some of the other larger items are emissions that are steered by biological activities and therefore difficult to control. In the nitrogen fertiliser production system there is a practical possibility to lower the GHG emissions. On a global scale, the production of nitrogen fertilisers is calculated to represent about 1% of anthropogenic GHG emissions (IFA, 2009a).

1.3 Aims and objectives

The general aim of this project was to investigate the possibilities and the consequences for the Swedish agricultural sector of producing nitrogen from renewable resources and agricultural raw materials. Specific objectives were to study the land use, energy use and GHG emissions from the production of ammonium nitrate based on wind power, biomass combined heat and power (CHP) and thermochemical gasification of biomass (Figure 2).

Ammonium nitrate was chosen since it is the most commonly used nitrogen fertiliser in Sweden[*]. An additional aim was to compare small-scale and large-scale production and to estimate the production costs.

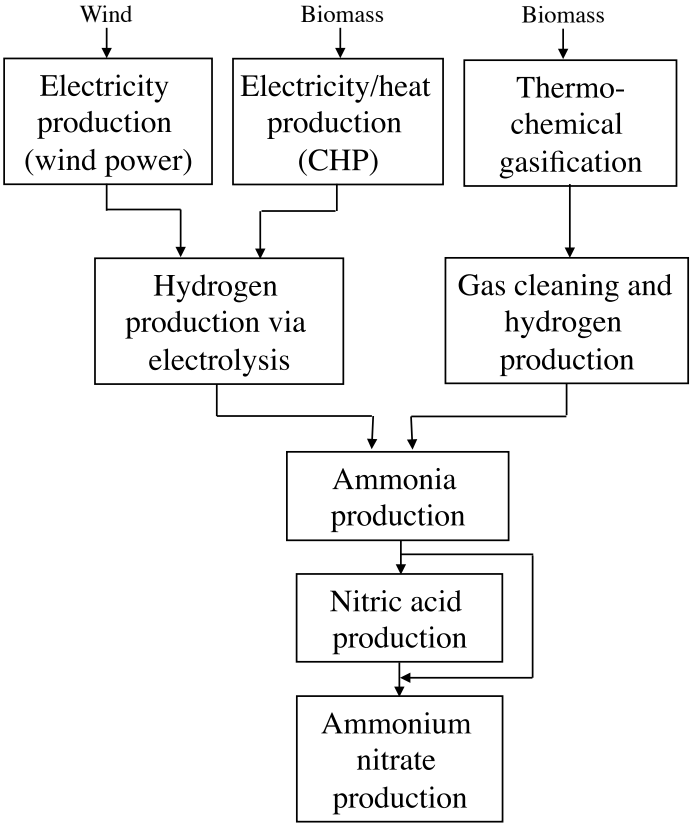

Figure 2. The nitrogen fertiliser production routes studied in this report. CHP: Combined heat and power.

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[*] Also sold as calcium ammonium nitrate which is produced in the same way as ammonium nitrates but with calcium added in the last step

2 BACKGROUND TO NITROGEN FERTILISERS

2.1 The beginning of nitrogen fertilisers in agriculture

Since the beginning of agriculture, cultivation of leguminous crops and recycling of organic waste has been a method for soil and nutrient conservation. However, it was not until the early 19th century that Justus von Liebig discovered nitrogen's role for crop productivity. Once this was clearly understood, the quest for new sources of nitrogen began. Bird excrement (guano) from a few tropical islands and sodium nitrate deposits in South America were found to have 30 times higher nitrogen content than common manure and were used as fertilisers. However, the demand was high and these resources were rapidly exhausted (Smil, 2001; Erisman et al., 2008).

During the second half of the 19th century nitrogen fertiliser production started from recovery of ammonia from the coking of coal, from calcium cyanamide and from fixation of atmospheric N_2 by electrical discharge. Fritz Haber was born 1868 in Germany. During the beginning of the 20th century, Fritz worked at the Technische Hochschule in Karlsruhe and started his research on ammonia synthesis. In 1909 he developed a laboratory scale high pressure ammonia synthesis working over an iron catalyst combining hydrogen and nitrogen gas. However, it was Carl Bosch who took the invention to commercial scale; today known as the Haber-Bosch process. The fuel and feedstock for the first commercial ammonia plant, situated in German Oppau, was coal. Since then, the use of nitrogen fertilisers has steadily increased (Smil, 2001).

2.2 Present use of nitrogen fertilisers

Due to variations in the purchase price of fertilisers, the sale prices of crops and agricultural practices, the amount of fertilisers used in Swedish agriculture varies. Nitrogen is sold both as straight fertilisers and as compound fertiliser products (Table 2). As can be seen in Table 3, the use of ammonium nitrate has increased during the last decade, while the use of calcium nitrate has substantially decreased. However, the total amount of nitrogen used in fertilisers in Sweden has decreased over recent decades (Figure 3).

In EU27, about 10.6 million ton nitrogen was sold as fertilisers during 2006/07. Of this, 43% was sold as ammonium nitrate and calcium ammonium nitrate, 18% as urea, 12% as N-solution and the rest as compound fertilisers. On a global scale, about 97 Gton nitrogen was sold; of this 54% was urea (EFMA, 2010).

Table 2. Sales of mineral fertilisers in Sweden, divided into straight and compound products, during the cropping season 2006/2007, expressed in plant nutrient content, thousand metric tons (SCB, 2008)

	Straight fertilisers	Compound fertilisers
Nitrogen (N)	98.7	68.4
Phosphorus (P)	0.2	13.5
Potassium (K)	2.0	29.2
Sulphur (S)	12.2	11.8

Table 3. Sales of straight mineral nitrogen fertilisers in Sweden divided into fertiliser type for the cropping seasons 1999/2000 and 2006/2007, expressed as ton of product (SJV, 2008b). The nitrogen content on weight basis is given in brackets.

	1999/2000	2006/2007
Calcium nitrate (15.5%)	286 217	57 775
Chilean nitrate of soda, $NaNO_3$ (16%)	952	-
Sodium ammonium nitrate (20%)	10 706	4 285
Ammonium sulphate (21%)	591	327
N 24 (24%)	-	75
Ammonium sulphate nitrate, N 26 (26%)	7 083	1 708
Calcium ammonium nitrate (26/27/28%)	205 869	287 566
Ammonium nitrate (34%)	55 011	30 980
N 32 (32%)	-	93
Urea (46%)	655	271
Nitrogen solutions (25/30%)	3 772	-
Anhydrous ammonia (82%)	116	15
Nitric acid (12%)	-	70
Total straight N fertilisers, ton products	*570 972*	*383 165*

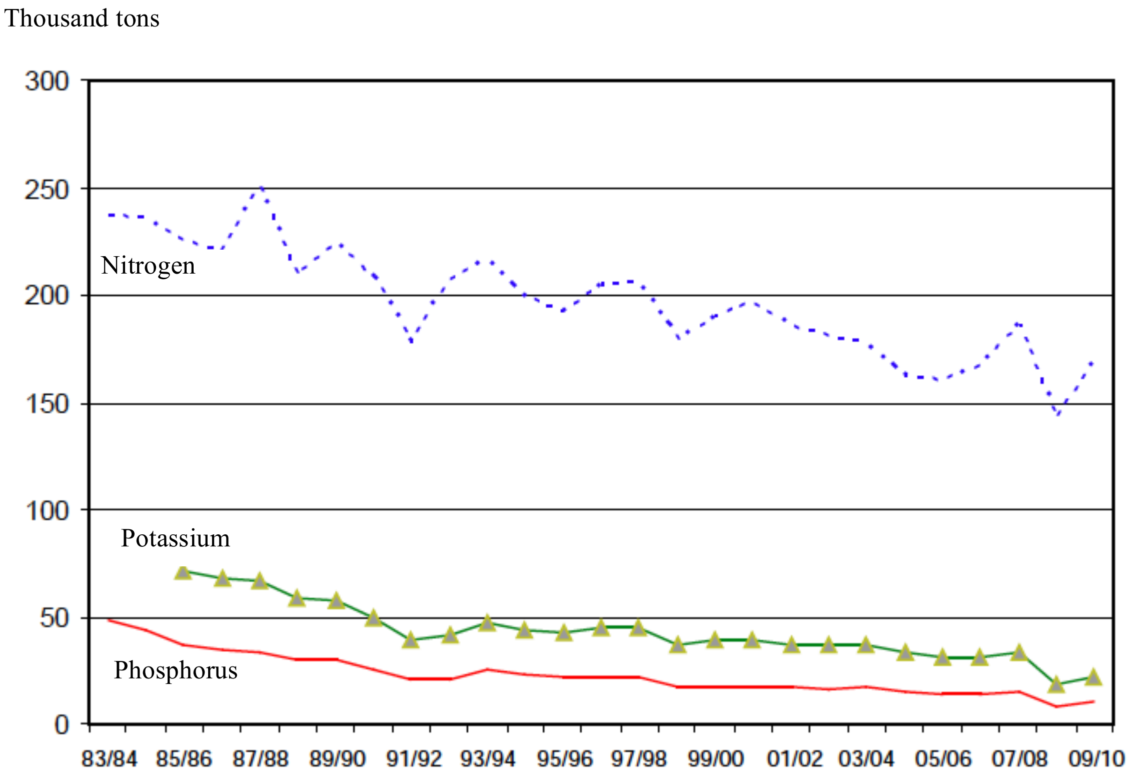

Figure 3. Sales of nitrogen, phosphorus and potassium in mineral fertilisers in Sweden over the last two decades (SJV, 2011).

2.3 Future use of nitrogen fertilisers

In Sweden, the use of nitrogen has decreased over recent decades. On a global scale, however, the use of nitrogen fertilisers is predicted to increase due to population growth, increased consumption of meat and increased use of biofuels (Smeets and Faaij, 2005; Erisman et al., 2008). Figure 4 shows the nitrogen requirement according to varying economic, demographic and technological developments, based on different scenarios described by IPCC (Erisman et al., 2008).

The A1 scenario assumes a world of very rapid economic growth, a global population that peaks mid-century, and rapid introduction of new and more efficient technologies. B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures towards a service and information economy. A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social and environmental sustainability.

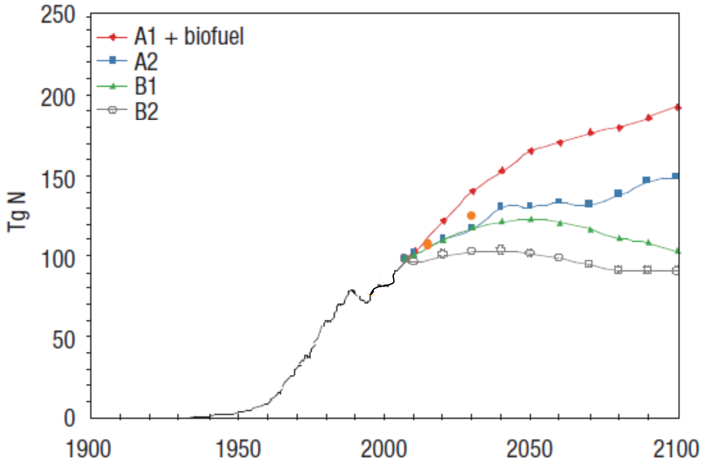

Figure 4. Predicted global nitrogen fertiliser consumption scenarios (Erisman et al., 2008). The A1, B1, A2 and B2 scenarios draw from the assumptions of the IPCC emission scenario (see text).

2.4 Production of ammonia

Ammonia is the building block for most mineral nitrogen products. All commercially produced ammonia at present uses the Haber-Bosch process, the overall reaction being:

$$N_2 + 3H_2 \rightarrow 2\ NH_3$$

While nitrogen is supplied from normal air, hydrogen is most commonly derived from natural gas, coal or heavy oils.

The synthesis of ammonia typically takes place over an iron catalyst at pressures of around 100-250 bar and temperature 350-550°C. The conversion efficiency to ammonia is low because of thermodynamic restrictions (20-30%) and the unreacted gas is recirculated. The ammonia that is formed is separated from the recycled gas by condensation. The reaction is exothermic, generating high pressure steam.

The principal stages of ammonia production based on natural gas are shown in Figure 5. After desulphurisation of the gas, reforming and shift conversion are carried out to produce the hydrogen needed for the process (Balat et al., 2009):

$CH_4 + H_2O \rightarrow CO + 3H_2$ (steam reforming)

$CO + H_2O \rightarrow CO_2 + H_2$ (water-gas shift)

The CO and CO_2 are poisonous for the ammonia synthesis catalyst and are therefore removed in the CO_2-removal and methanation step.

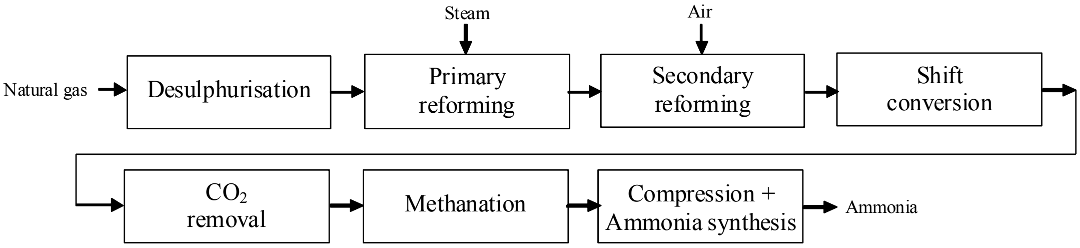

Figure 5. Principal stages of ammonia production with natural gas as the feedstock. The hydrogen needed for the ammonia process is derived from the natural gas and the nitrogen from the air (Smil, 2001).

The required hydrogen can also be produced by thermal gasification of hydrocarbons such as coal (mainly done in China), fuel oil (EU, China, India) or naphtha (India). Thermal gasification (sometimes referred to as partial oxidation) means that the hydrocarbons are combusted, but with a shortage of oxidant (air, oxygen and/or steam). Instead of producing heat as in normal combustion, the product is an energy-rich gas. Depending on the technical setup of the gasification process and the raw material, the gas consist of different amounts of carbon monoxide, hydrogen, methane, nitrogen, carbon dioxide, steam and some trace gases. The gas needs several steps of cleaning, as well as shift conversion and CO_2 removal to extract the hydrogen before ammonia synthesis (Figure 6).

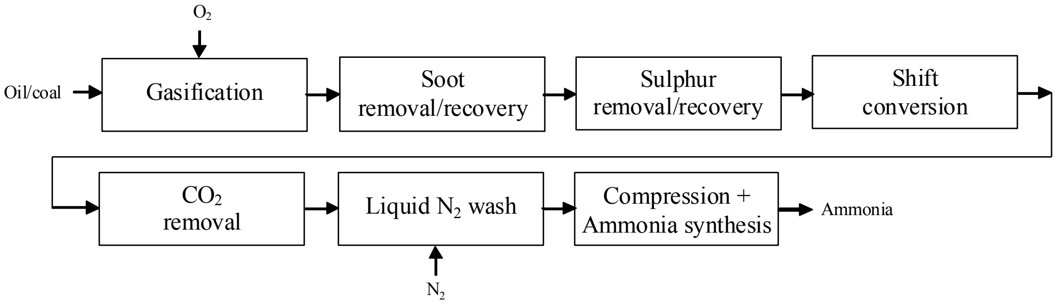

Figure 6. Principal stages of ammonia production based on gasification of hydrocarbons. The oxygen for gasification and the nitrogen for ammonia synthesis can be supplied via an air separation unit (EFMA, 2000).

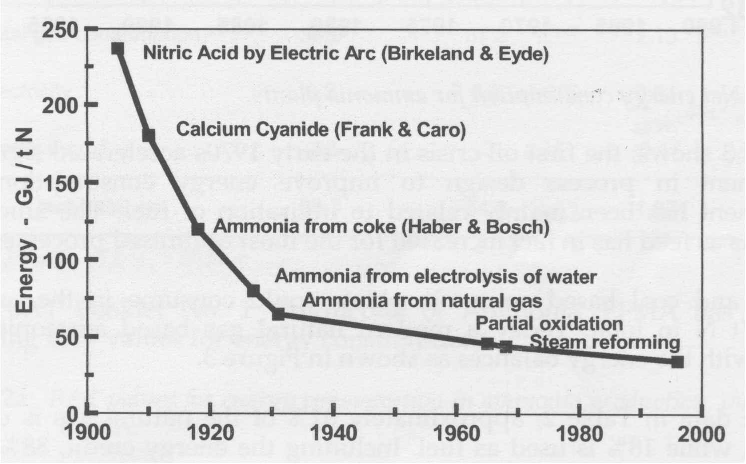

Figure 7. Historical changes in the energy requirement for N fertiliser production (Jenssen and Kongshaug, 2003).

The energy requirement has dramatically decreased over time from about 55 GJ/metric ton of ammonia produced in the 1950s to 35 GJ/ton in the 1970s, while nowadays the best plants using natural gas as feedstock need only 28 GJ/ton (Figure 7). The thermodynamic minimum energy requirement is 20 GJ/ton NH_3 (Smil, 2001). Energy requirement for best technology in practice using other raw material is presented in Table 4. Best available technology here refers to available commercial scale technique that can be implemented also considering economical constraints. According to the International Fertilizer Industry Association about 67% of global ammonia production is based on natural gas, 27% on coal while fuel oil and naphtha account for 5% (IFA, 2009a). Since a number of old plants are still in operation, the global average energy requirement was in 2008 around 37 GJ/ ton ammonia (ranging from 27-58 GJ/ton NH_3) (IFA, 2009b).

Table 4. Comparison of best available process technology for ammonia production (IFA, 2009a)

Energy source	Process	Energy requirement GJ/ton NH_3 (GJ/ton NH_3-N)
Natural gas	Steam reforming	28 (34)
Naphtha	Steam reforming	35 (43)
Heavy fuel oil	Partial oxidation	38 (46)
Coal	Partial oxidation	42 (51)

The GHG emissions associated with ammonia production are mainly CO_2 in the flue gases from the reforming and CO_2 removal section, originating from the carbon in the fossil fuels used. In partial oxidation plants, CO_2 can also be emitted from power steam production in auxiliary boilers (EFMA, 2000). Emissions figures are presented in Table 5.

2.5 Production of fertiliser products

Once ammonia is produced, it can be used to make straight nitrogen fertilisers or together with phosphate, potassium or micronutrients to make compound fertilisers (Figure 8).

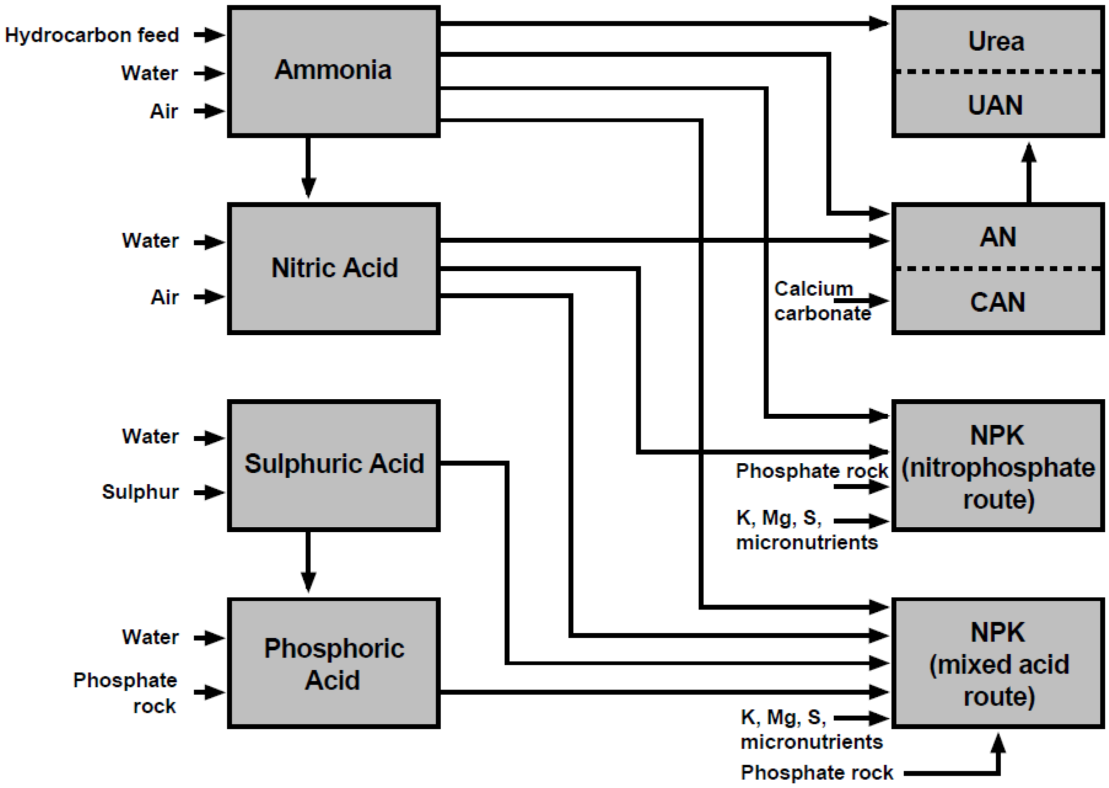

Figure 8. Production route for commonly used fertilisers (EFMA, 2000). UAN=Urea Ammonium Nitrate (Solution), AN=Ammonium Nitrate, CAN= Calcium Ammonium Nitrate, NPK= Compound fertiliser containing Nitrogen, Phosphate and Potash.

In this study, production of ammonium nitrate was investigated. To produce ammonium nitrate, about half the ammonia produced is first processed to nitric acid (the other half is used in the next step to produce ammonium nitrate solution). Nitric acid is produced by the exothermic reaction of ammonia and air over a catalyst and the absorption of the gas produced in water. By neutralising the nitric acid with the remainder of the ammonia, an ammonium nitrate solution is produced (exothermic reaction). The solution is then evaporated to remove water and the ammonium nitrate can be prilled or granulated to a final product.

In the production of nitric acid, nitrous oxide (N_2O), which is a strong GHG, is generated. In recent years, catalytic filters have been installed in a number of plants to remove the nitrous oxides. This can greatly reduce the GHG emissions from ammonium nitrate production (Table 5).

Table 5. Greenhouse gas emissions from production of ammonia and ammonium nitrate (kg CO_2-eq/kg N), based on IFA (2009a).

	World average	Using best available technology when building new plant
Ammonia – natural gas	2.6	1.9
Ammonia – coal	5.0	4.6
Ammonium nitrate, natural gas-based ammonia (accumulated emissions)	7.3	2.8
Ammonium nitrate, coal-based ammonia (accumulated emissions)	9.7	5.5

2.6 Production of ammonia based on renewable energy

The hydrogen needed for ammonia synthesis can also be produced from renewable resources. There are four main options available for the production of renewable hydrogen for use in ammonia production (Chum and Overend, 2001; Ni et al., 2006):

1. Electrolysis based on renewable electricity.
2. Reforming of biogas.
3. Thermal conversion of biomass (pyrolysis and gasification).
4. Collection of hydrogen produced by algae and photosynthesising organisms.

In this study, electrolysis (1) and thermal gasification (3) were studied.

Electrolysis is the process by which water is split into hydrogen and oxygen with the aid of electricity. Thermal gasification (partial oxidation) means that the biomass is combusted, but with a shortage of oxidant (air, oxygen and/or steam). Instead of producing heat as in normal combustion, the product is an energy-rich gas. The process is further described in Appendix A.

There have been some production facilities utilising electrolysis to produce hydrogen and then ammonia. In the 1940s and 1950s, several small-scale electrolytic ammonia plants were built in for example Norway, Egypt, Peru, Iceland and Zimbabwe. However, most of these have been decommissioned (UNIDO/IFDC, 1998). Between 1948 and 1990, the company Norsk Hydro operated a hydropower-driven electrolyser with 150 MW capacity, the hydrogen being used to produce ammonia. During the oil crisis in the 1970s and 1980s, production of ammonia on a small scale was considered as a way of reducing the dependency on fossil oil. Some studies were carried out on electrolysis-based ammonia production, see for example Dubey (1978), Jourdan and Roguenant, (1979) and Grundt and Christiansen (1982).

At present, the concept of small-scale renewable ammonia production is becoming interesting again, as a measure to reduce fossil fuel dependency and also reduce GHG emissions. In Minnesota, USA, a plant is currently being commissioned that will produce 1 ton per day ammonia from wind-powered electrolysis (New Energy and Fuel, 2010).

The concept of nitrogen fertilisers produced by reforming of biogas (2) and thermal gasification (3) has been studied by Ahlgren et al. (2008). However, collection of hydrogen produced by algae etc. (4) is very high-tech and the hydrogen production is so far only at laboratory-scale. As far as we know, the system has not been considered for ammonia production.

3 METHODS

3.1 Scenario construction

The aim of the present study was to evaluate the land use, energy use and GHG emissions from the production of ammonium nitrate based on renewable resources using life cycle assessment methodology.

However, a large part of the study consisted of describing reasonable technical solutions for the production of 'green fertilisers' and modelling the inputs and outputs in the processes. The description of the scenarios was prepared based on literature studies, but also on discussions with reference individuals associated with the project (see Acknowledgments). All modelling (processes, energy use, land use, GHG emissions, costs) was done in a spread sheet.

3.2 General introduction to life cycle assessment methodology

Life cycle assessment (LCA) is a methodology used for studying the potential impact on the environment caused by a chosen product, service or system. The product is followed through its entire life cycle. The amount of energy needed to produce the specific product and the environmental impact are calculated. The life cycle assessment is limited by its outer system boundaries (Figure 9). The energy and material flows across the boundaries are looked upon as inputs (resources) and outputs (emissions).

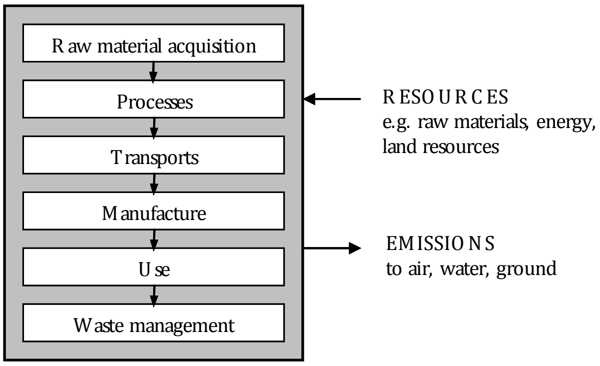

Figure 9. The life cycle model. Based on Baumann and Tillman (2004).

The methodology for conducting a life cycle assessment is standardised in ISO 14040 and 14044 series. According to this standard, a life cycle assessment consists of four phases (Figure 10). The first phase includes defining a goal and scope. This should include a description of why the LCA is being carried out, the boundaries of the system, the functional unit and the allocation procedure chosen. The second phase of an LCA is the inventory analysis, i.e. gathering of data and calculations to quantify inputs and outputs. The third phase is the impact assessment, where the data from the inventory analysis are related to specific environmental hazard parameters (for example CO_2-equivalents). The fourth phase is interpretation, where the aim is to analyse the results of the study, evaluate and reach conclusions and recommendations (ISO, 2006a, 2006b). In an LCA study, the phases are not carried out one by one but in an iterative process across the different phases.

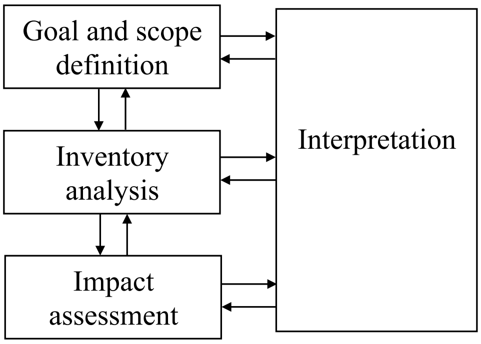

Figure 10. Stages of an LCA (ISO, 2006a).

There are two main types of LCA studies; attributional and consequential. The attributional LCA study (sometimes also referred to as accounting type LCA) focuses on describing the flows to and from a studied life cycle. The consequential LCA (sometimes also referred to as change-orientated type LCA) focuses on describing how flows will change in response to possible decisions. Some authors state that attributional LCA are mainly used for existing systems, while consequential LCA are used for future changes (for example Baumann and Tillman, 2004). However as Finnveden et al. (2009) point out, both types of LCA can be used for evaluating past, current and future systems.

The type of LCA carried out has an impact on many of the methodological choices in an LCA. For example in handling of by-products, the attributional LCA uses an allocation based on mass, monetary value, etc. In a consequential LCA, a system expansion is instead often the choice, e.g. trying to determine the consequences of a new by-product appearing on the market. It also affects the choice of data; in a consequential LCA marginal data are used as it studies a change in a system, while an attributional LCA uses average data.

For LCA studies including use of biomass, the use of land must be included. When growing crops for energy purposes, land is needed. Quantifying emissions connected to loss or accumulation of carbon at the site of cultivation of the raw material can be referred to as the direct land use change.

In recent years, however, there have been calls to also include indirect land use. If the land used for energy crops was previously used for other activities, for example cereal production or pasture, it is probable that the demand for these products will still continue to exist. The demand for the products previously produced from the land now occupied by energy crops can be met by increasing the yields on the same land, or by moving the activities to another location. This moving of activities can cause land use changes, for example by utilisation of previously uncultivated land within the country under study or outside that country (Cherubini, 2010). However, quantification of indirect land use is very difficult and requires the use of economic equilibrium models and the results are associated with high uncertainty.

3.3 Chosen impact categories in the study

There are many impact categories that can be included in an LCA. In general, the categories can be divided into three main groups; resource use, human health and ecological consequences (Baumann and Tillman, 2004).

In this study, the resources categories studied were energy and land use. Energy analysis is often included as a step in the execution of a life cycle assessment, calculating the cumulative energy demand, often divided into renewable primary energy carriers (e.g. biomass) and non-renewable primary energy carriers (e.g. coal, oil, gas) (Jungmeier et al., 2003). The energy demand is often expressed as primary energy, which is defined as the energy extracted from the natural system before transformation to other energy carriers (Baumann & Tillman, 2004). In this study the energy use was expressed as primary fossil energy use. The primary energy factors are presented in Table 6.

Table 6. Primary energy factors used in the study

Diesel	Natural gas	Wind power (generated)	Wind power (distributed)	District heating (oil)	Electricity (coal)
1.06[1]	1.06[1]	0.047[2]	0.055[2]	1.27[3]	2.72[3]

[1] Factor for production and distribution (Uppenberg et al., 2001).

[2] Factor for manufacture and decommissioning. Distributed means grid losses are included (Vattenfall, 2010).

[3] Including production, distribution and conversion losses (Uppenberg et al., 2001).

In the biomass scenarios, land is required for cultivation or collection of raw material. The land use is expressed as the number of hectares needed per functional unit (FU). However, it also important to account for any changes in the soil carbon content in the GHG balance. Therefore the former use of the land must be established. It is also important to establish whether any other land use activities have changed due to the raw material cultivation, for example whether a previous crop cultivation has been displaced to another location (indirect land use); this is dealt with in the sensitivity analyses.

The ecological consequence impact category investigated in this study was global warming potential. The characterisation factors were chosen for a 100-year perspective; fossil CO_2: 1, CH_4: 25 and N_2O: 298 (IPCC, 2007). The impact on human health was not assessed.

3.4 Functional unit in the study

In principle, all nitrogen fertilisers on the market today are based on fossil fuel. By producing nitrogen fertilisers based on renewable resources, the production of fossil fuel-based fertilisers can be avoided. The functional unit in this study was set to the production of 1 kg of fertiliser nitrogen based on renewable resources as ammonium nitrate (33.5% N) at the gate of the production facility, assuming that the nitrogen produced avoids the production of a fossil fuel-based alternative.

3.5 Overview of scenarios studied

Table 7 presents an overview of the five scenarios studied. In scenarios 1 and 2, wind power was assumed to be used to power an electrolysis process, producing the hydrogen needed for fertiliser production. Scenario 1 studied small-scale production, while scenario 2 studied large-scale production. In scenarios 3 and 4, combustion of biomass to produce heat and electricity was studied. In scenario 3 a new plant was assumed to be commissioned. Biomass then needs to be supplied from new land (this will give rise to land use change emissions, see further description in section 4.3). Scenario 4 assumed that the nitrogen fertiliser production is integrated into an existing CHP plant. The biomass used therefore does not need to be taken from new land. However, the electricity previously sold to the grid is now used for fertiliser production. This means that the electricity no longer put on the grid must be produced elsewhere (Figure 11). In scenario 5, a new plant utilising thermal gasification technology to produce hydrogen for fertiliser production was studied. In comparison with present commercial-scale production sites, all scenarios studied can be considered small-scale. Thus the terms small-scale and large-scale production (Table 7) are used to distinguish differences in scale between the five scenarios and not in comparison with present production.

Table 7. Overview of scenarios 1 to 5

Scenario	Scale	Technology	Short description
1	Small	Wind power - electrolysis - fertiliser production	New plant, wind power and fertiliser production at same location.
2	Large	Wind power - electrolysis - fertiliser production	New wind power connected to grid. New fertiliser plant can be located elsewhere, preferably close to end-user or harbour.
3	Large	Combustion Salix/straw - electrolysis - fertiliser production	New plant located close to raw material supply. Surplus heat used for district heating, replacing marginal heating.
4	Large	Existing biomass CHP - electrolysis - fertiliser production	Integrated fertiliser production in existing CHP (combustion of forest residues). The electricity no longer produced has to be replaced by production elsewhere. More heat than before integration will be produced, the extra heat replaces marginal alternative.
5	Large	Thermochemical gasification - fertiliser production	New plant located close to raw material supply. Electricity surplus sold to the grid, replacing marginal alternative.

The green fertilisers produced were assumed to outcompete other types of nitrogen (Figure 11). The question is what type of fertiliser is the green nitrogen replacing. This is important, since all CO_2 savings are relative to this. This question is also vital for the heat and electricity by-product credits.

Many LCA practitioners argue that when modelling a change, marginal data should be used, as it is the marginal production that is first affected by market changes (Ekvall and Weidema, 2004). In an energy use context this would typically be a fossil-based alternative. However this may not always be the case. As Finnveden (2008) points out, due to regulatory systems (such as the EU CO_2 cap), the marginal might be a renewable fuel, or more likely a complex mix of different types of energy sources. A number of energy prediction models are available to establish the marginal energy production, but it tends to be very difficult to model the effects in a proper way and the results are highly uncertain (Mathiesen et al., 2009). To highlight this uncertainty, Finnveden (2008) recommends that two scenarios be used in LCAs, one high CO_2 emission marginal alternative and one with low CO_2 emissions.

For the sake of simplicity, in this study we assumed that fossil oil is the marginal production for district heating and coal for electricity. For nitrogen fertilisers the marginal production was assumed to be an older natural gas plant without nitrous oxide removal. In the sensitivity analysis we investigated how the results are influenced by different assumptions of marginal production.

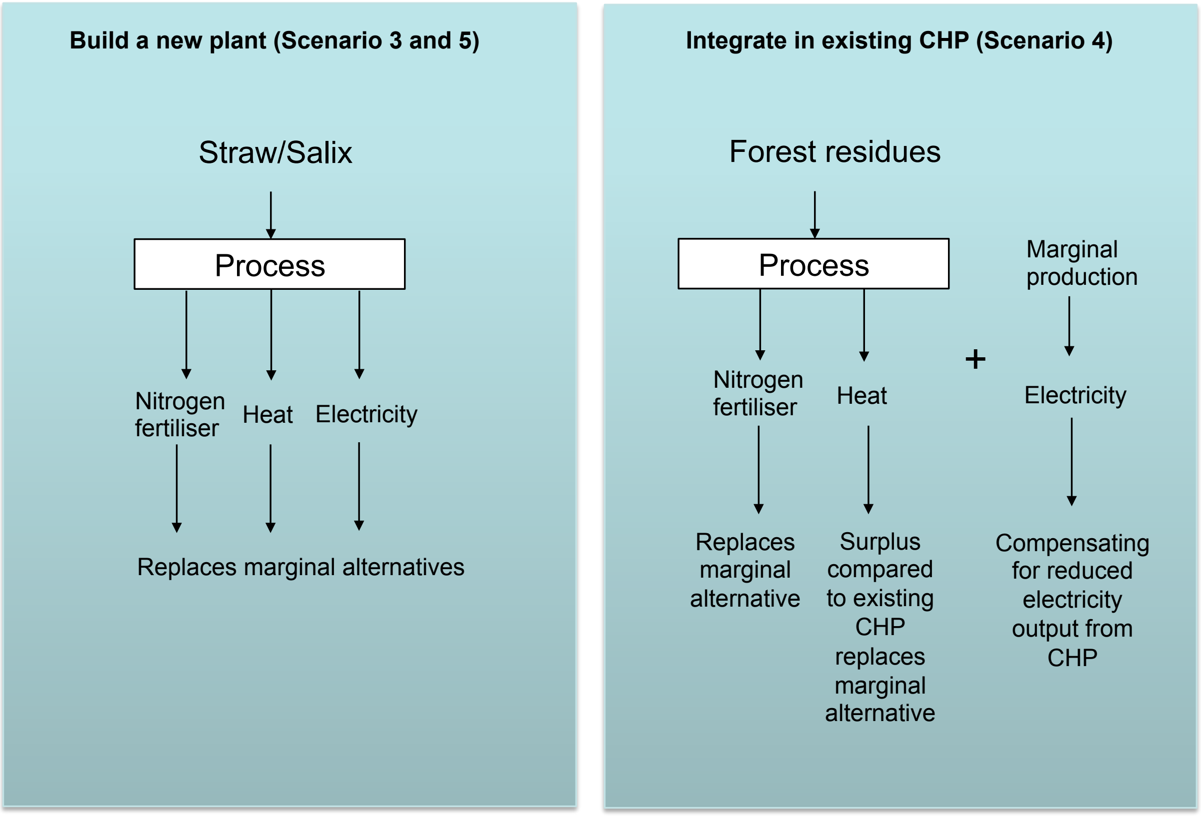

Figure 11. Visual description of calculation assumptions. In scenarios 3 and 5, it was assumed that raw material previously not harvested (straw) or planted on marginal land (Salix) is used. The products then replace marginal alternatives on the market. In scenario 4 it was assumed that the nitrogen production is integrated within an existing CHP (combined heat and power) plant. The electricity previously sold to the grid is then utilised for nitrogen production. This missing electricity on the market was assumed to be compensated for by marginal production. In scenario 4, only the excess heat compared with the existing CHP plant was accounted for.

3.6 System boundaries and delimitations

The emissions of GHG were quantified from 'cradle-to-gate', i.e. all the emissions stemming from raw material acquisition to ammonium nitrate product at the factory gate were included. The use of the fertiliser was therefore not included. However, in the biomass scenarios fertilisers are needed for cultivation. Therefore it was assumed that part of the ammonium nitrate produced is returned to the plantation/field. For Salix plantations, the amount of returned nitrogen was according to the fertiliser recommendations (Gustafsson et al., 2007), while for straw and forest residues the amount of returned nitrogen was calculated as the amount of nitrogen removed with the straw/residue (Phyllis, 2010). The emissions arising from the use of those fertilisers (mainly nitrous oxide from soil) were included in the calculations.

Furthermore, bottom ash from combustion and gasification, which contains valuable phosphorus and potassium, was assumed to be returned to the growing site. The return of ash to agricultural fields is not regulated by Swedish law. However, there are regulations for spreading of sewage sludge, which could serve as guidelines for upper limit of heavy metals (Gruvaeus and Marmolin, 2007).

In the electrolysis process, water is split to produce hydrogen. As a by-product, oxygen is formed. In the air separation unit used in the gasification scenarios to produce nitrogen, oxygen is also formed as a by-product. The oxygen can be sold to other industries, but it is not certain that there is a market for this, so it was not given any value in this study.

Emissions from production of capital goods such as machinery and buildings were not included in the bioenergy calculations, since in previous studies they have been found to have little impact on the results when converting biomass to fuel (or, as in this case, to nitrogen) (Bernesson et al., 2004, 2006). In the wind power scenarios, however, the manufacturing and decommissioning were included.

3.7 Production costs

Production costs of AN fertilisers were calculated for two of the scenarios, scenarios 1 and 3.

Electricity is used by all processes in the AN fertiliser production chain and was calculated separately in order to show the economic impact on total production costs from electricity generation. The costs for other processes in the AN production chain are shown excluding electricity costs.

Annual costs for producing AN fertiliser were estimated for fixed costs and costs for operation and maintenance (O&M). The base year for the economic calculations was set to 2010 and all costs collected from older sources were allocated to this year. An inflation calculator was used to recalculate US data to 2010 (Inflation calculator, 2011) using US consumer price indexes (CPI) for recalculation. Swedish costs were recalculated to 2010 using an inflation calculator from SCB (SCB, 2011). Costs in currencies other than SEK were first allocated to 2010, then yearly average currency data from Riksbanken (2011) were used to obtain cost in SEK from USD.

For electricity generation, the annual costs of the total investment cost (I) were calculated using the annuity method. The annuity method uses rate of interest (R) set to 6% and depreciation time (T) of 20 years to calculate the annuity factor (n) according to Equation 1:

$$n = \frac{R}{1 + (1 - R)^{-T}} \qquad \text{Equation 1}$$

The annuity factor (n) multiplied by total investment costs (I) gives the annual fixed costs (A) (Equation 2). Costs for O&M are calculated on an annual basis and then added to the annual fixed costs.

$$A = I * n \qquad \text{Equation 2}$$

In the case of ammonia, nitric acid and AN fertiliser production, total annual costs (both fixed and O&M) for different plant sizes were taken from UNIDO (1983). These data were used instead of using the annuity method to calculate the electricity costs.

In the case of small-scale production of ammonia, nitric acid and AN fertiliser, data for large-scale production were scaled down to fit small-scale production using cost and scale factors (Gerrard, 2000; Remer et al., 2008). The total cost of a proposed plant (C) with size (S) can be estimated from the total cost of a similar reference plant (C_r) with size (S_r) using Equation 3. The scale exponent (n) can be derived from historical data for similar plants and is usually in the range 0.4-0.8, typically 0.65 (Gerrard, 2000).

$$\frac{C}{C_r} = \left(\frac{S}{S_r}\right)^n$$

Equation 3

4 INVENTORY OF ENERGY AND EMISSION DATA

All data on emissions were taken from the literature. For a detailed description of the technical assumptions, see Appendix A and B.

4.1 Wind power

The emissions from wind power production arise in three phases: construction, operation and decommissioning (Tremeac and Meunier, 2009). A review of LCA studies on wind power was carried out by Varun et al. (2009). The GHG emissions varied between 9.7 and 39.4 g CO_2-eq per kWh, with one study of small-scale wind power in Japan reporting 123.7 g CO_2-eq per kWh. In this study we chose to use data from an EPD (Environmental Product Declaration) carried out by Vattenfall (2010). The GHG emissions per kWh generated at the wind power plant are reported to be 15 g CO_2-eq per kWh. The GHG emissions after distribution assuming a 5% loss are 17 g CO_2-eq per kWh.

In the small-scale wind power to nitrogen fertiliser system studied, the figure for generated electricity was assumed, while the distributed figure was used in the large-scale scenario.

4.2 Cultivation/collection of biomass raw material

The yield of straw was set to 4.3 ton dry matter per hectare and year. Data on the energy use for windrowing, baling and collection were taken from Nilsson (1997).

For Salix, a yield of 10 ton dry matter per hectare and year was assumed. Data on energy use for planting, weed control, harvest etc. were taken from Börjesson (2006).

For forest residues, it was assumed that 32 wet ton of residues per hectare are collected after final felling (RecAsh, 2009). This is an average yield after final felling of a mix of rich and poor spruce and pine stands. With a rotation time of 80 years, this on average gives 217 kg dry matter per hectare and year. Data on energy for collecting, bundling etc. were taken from Lindholm (2010).

4.3 Land use and soil carbon

4.3.1 Straw

In scenarios 3 and 5, straw was assumed to be used as raw material. Harvesting straw leads to no actual land use as it is a by-product from cereal cultivation. This is under the assumption that the straw is previously not utilised for any other purpose and therefore has no indirect effects on land use[*].

However, harvesting straw can have an impact on the soil carbon content. The carbon no longer sequestered in the soil due to straw harvest has to be accounted for in the GHG balance. It is the difference on a long-term basis in soil carbon content between harvesting and not harvesting straw that should be counted. Straw incorporated into soil will decompose, but part will be transferred to the long-term soil carbon pool. The rate of decomposition

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[*] There are no recent surveys of straw utilisation in Sweden, the latest one dating from 1997. In that, it was estimated that 1% of the straw was burned on field, 64% incorporated in soil and 35% harvested (utilised as feed, litter and energy) (SCB, 1999). Here we assume that there is enough straw available for harvesting that is currently not utilised.

depends on many factors, such as the characteristics of the soil (e.g. structure, pH, initial carbon) and climate (e.g. temperature, humidity) and farming practices (e.g. rotation, tillage) (Johansson, 1994).

Trials with radioactive labelling in Sweden show that only 5-10% of incorporated carbon in straw is left in the soil after 10-20 years (Mattsson and Larsson, 2005). Assuming a straw harvest of 4 ton and a carbon content of 50% results in between 200 and 400 kg C left after 10-20 years. Assuming a longer time perspective would reduce the amount of carbon left. In a study by Johansson (1994), a model for soil carbon with and without straw removal showed a difference of 5300 kg C per hectare and year after 100 years (53 kg C difference per year on average). Based on long-term field results (Röing et al., 2005), we concluded that removal of straw has no impact on topsoil C. In yet another study modelling soil C removal, a variation of 78-385 kg C/ha and year was observed (Saffih-Hdadi and Mary, 2008).

In conclusion, the effect of straw harvest on soil C is difficult to assess and is dependent on local factors and the time period studied. In this study we assumed that removing straw results in a reduction of 150 kg C/ha and year, over a period of about 30–50 years after which the soil carbon level will have reached a new steady state (based on Börjesson and Tufvesson (2011)).

4.3.2 Salix

Salix was studied as raw material in scenarios 2 and 5. At present, only 15 000 ha of Salix are planted in Sweden. However, the potential is reported to be as large as 200 000 ha (SOU, 2007). In this study we assumed that the plantation of Salix will take place on land previously not used for other purposes. One good reason for this is that the land currently used for crops is most likely the best farm land. It would not be economically optimal to plant Salix on the best farm land, but rather on other types of land.

At present, about 5.8% (equal to 153 300 ha) of Swedish farm land is under fallow (SJV, 2008c). There is also a great deal of abandoned farm land, since the cultivated area has declined by about 300 000 hectares since the 1970s (SOU, 2007). According to a study by the Swedish Board of Agriculture, there is also an overproduction of 200 000-300 000 hectares of ley which is not utilised (SJV, 2008c). It is reasonable to believe that increased planting of Salix will take place on all these different types of land.

Planting Salix can have both negative and positive effects on soil carbon content. A combination of different previous land uses was assumed here (Table 8).

Table 8. Soil carbon increase when Salix is planted on different types of land and the assumed share of each land type converted

	Fallow farm land (mineral soil)	Fallow farm land (organic soil)	Previously ley	Abandoned farm land
Soil carbon increase (kg C/ha year)	500[1]	1700[2]	0[1]	0[3]
Assumed share of land used to plant Salix	50%	5%	20%	20%

[1] Ref: Börjesson (1999)

[2] Ref: Berglund and Berglund (2010)

[3] The quality of abandoned farm land varies a great deal, which makes it difficult to assess the effect of cultivating Salix. We assumed that there is no increase in soil carbon.

The average soil carbon stock change for planting Salix in Sweden was calculated to be an average increase of 335 kg C/ha and year (1228 kg CO_2-eq/ha and year) based on data in Table 8. This is assumed over a period of about 30–50 years after which the soil carbon level will have reached a new steady state. Similar to straw removal, the uncertainty in carbon stock changes due to Salix plantation is very large and great variations are reported in the literature. Therefore this issue is further dealt with in the sensitivity analysis.

4.3.3 Forest residues

In scenario 4, forest residues are used as the raw material for nitrogen fertiliser production. Forest residues contain some carbon that would have been left in the forest if not utilised. In a study by Lindholm (2010), the effect on the soil carbon content when removing forest residues was analysed using a model and proved to be very dependent on the time frame assumed. Over a long time period (2-3 rotations or 240 years) the decrease in soil C was calculated to between 2.9 and 3.5 kg C/ha and year when removing logging residues after the final fellings. Other studies have found higher decreases, 17-50 kg C/ha and year (see review of other studies in Lindholm (2010)). In the present study an average loss of 3.2 kg soil C/ha and year was assumed in the base case scenario over a longer time period (2-3 rotations).

This means that the time frame for soil carbon changes is different for the forest residue scenario compared to the straw and Salix scenarios. The reasoning behind this can be compared to the IPCC Guidelines where a stock change perspective is applied and the change in soil C is divided by a plantations life-time, IPCC has a default value of 20 years (IPCC, 2006). However, here we have used data for Salix and forest residues stretching out for two rotation periods. For straw, the rotation period argument can not be used, but we assumed same as for Salix since they both were assumed to effect farm land. There is no consensus on how soil carbon changes in bioenergy systems should be calculated over time (Lindholm, 2010), and the approach here applied can of course be discussed.

4.4 Transport of biomass raw material

The plants utilising biomass as raw material were assumed to be located in an area where there is a large resource available. The transport distance for biomass was calculated using the model described in Nilsson (1995) and Overend (1982). According to this, the area from which biomass is collected was assumed to be circular, with the plant in the centre. The average transportation distance is dependent on the biomass requirements of the production plant, a road tortuosity factor and the available amount of biomass in the area.

4.5 Nitrogen fertiliser production

We studied two main routes for fertiliser production; via electrolysis of water and via thermal gasification (see Figure 2). Both of these processes aim to produce the hydrogen needed for ammonia synthesis, in which hydrogen and nitrogen from normal air are combined.

4.5.1 Hydrogen production via electrolysis

Four different electrolysis scenarios were studied, one small-scale (scenario 1) and three large-scale (scenarios 2, 3 and 4).

In the small-scale scenario, low temperature alkaline electrolysis was assumed and the electricity use set to 180 MJ per kg hydrogen (Zeng and Zhang, 2010). For large-scale production solid oxide high temperature electrolysis was assumed, utilising electricity (120 MJ/kg H_2) and steam (28 MJ/kg H_2), data collected from Zeng and Zhang (2010).

4.5.2 Hydrogen production via thermal gasification

For the thermochemical conversion route, only large-scale production was considered (scenario 5). The hydrogen yield and electricity requirement were based on data found in Hamelinck and Faaij (2002) and emissions data from Edwards et al. (2010).

4.5.3 Ammonia synthesis

For the large-scale scenarios, yields, energy consumption and steam production for ammonia synthesis were assumed to be similar to those of a natural gas-based system; data were taken from Dybkjær (2005) and Uhde (2011). The nitrogen required was assumed to be produced in a cryogenic air separation plant.

There are almost no small-scale ammonia facilities, not so much because of technical difficulties but due to economies of scale. A small-scale facility cannot invest in turbines and can therefore not fully utilise the high pressure steam formed in different parts of the process. Instead pumps, compressors etc. must be driven by electricity (UNIDO/IFDC, 1998; Noelker, 2010). Nitrogen was assumed to be produced by pressure swing adsorption and a De-oxo unit. An energy requirement of 3.3 MJ/kg NH_3 was assumed for the ammonia production step (for air separation, compression, ammonia synthesis loop etc) (see further description in Appendix A).

4.5.4 Nitric acid production

Nitric acid is produced by the exothermic reaction of ammonia and air over a catalyst and the absorption of the product gas in water. Data for yields, electricity use and steam production were taken from IPPC (2007) and Saigne (1993). One can suspect that there will be larger heat losses per mass unit in a small scale system. However, due to lack of data, no distinction was made between large- and small-scale production. It was however assumed that in the small scale process, non of the steam could be utilised for electricity generation.

In the reaction, nitrous oxides (N_2O) are generated. However, using a combination of abatement techniques, the N_2O emissions from a modern new built plant can be limited to between 0.12 and 0.6 kg N_2O/ton nitric acid (100%) according to IPPC (2007). Here we assumed 0.6 kg/ton nitric acid (100%) in all scenarios, which recalculated can be expressed as 2.8 g N_2O/kg N. Due to lack of data, no distinction was made between large- and small-scale production.

4.5.5 *Ammonium nitrate production*

By neutralising the nitric acid with the remainder of the ammonia, an ammonium nitrate solution is produced (exothermic reaction). The solution is evaporated to remove water. A modern plant produces enough heat in the neutralisation to remove the water and no additional heat is needed (Jenssen and Kongshaug, 2003). The ammonium nitrate is thereafter granulated. The electricity requirement is relatively small, 25 kWh/ton ammonium nitrate produced (EFMA, 2000). Due to lack of data, no distinction was made between large- and small-scale production.

4.6 Energy credit/debt

In some scenarios there will be a surplus of heat and/or electricity. In the scenario where nitrogen production is integrated into an existing CHP, the electricity previously sold to the electric grid will be used for the electrolysis process and the missing electricity will need to be produced elsewhere. In this study we assumed that fossil oil is the marginal production for district heating and coal for electricity (emissions data taken from Uppenberg et al., 2001).

4.7 Replaced fossil nitrogen fertiliser

For nitrogen fertilisers the marginal production was assumed to be an older natural gas plant without nitrous oxide removal, with emissions of 7.3 kg CO_2-eq/kg N equivalent to the world average in Table 5 (data taken from IFA, 2009a).

5 INPUT DATA FOR ESTIMATION OF PRODUCTION COSTS

All data on costs were taken from the literature. For a description of the technical assumptions, see the preceding section and Appendix A.

5.1 Wind power

Using data from Hansson et al. (2007) and Wizelius (2009), the costs for producing land-based wind power in Sweden can be calculated (Table 9). Fixed costs are calculated for 20 years depreciation time with 6% interest. This equals an electricity production cost of 310 SEK per MWh. Annual average spot price of electricity in 2010 was 506 SEK per MWh (Nord Pool, 2011).

Table 9. Yearly fixed and running costs for a wind power unit with an effect of 2 MW

	Costs	Unit
Annual investment cost	559	SEK/MWh_{el}
Costs for operation and maintenance	51	SEK/MWh_{el}
Green certificate	-295	SEK/MWh_{el}
Total costs	315	SEK/MWh_{el}

5.2 Power generation in CHP

In the case of large-scale production of ammonia, biomass is combusted in a CHP plant. Electricity and steam are used in all processes from electrolysis, ammonia and nitric acid production and for producing AN fertilisers. The accumulated daily electricity requirement is 1 400 MWh. This equals a CHP plant producing 78 MW of electricity and 195 MW heat. The plant uses 1 314 GWh of fuel per annum. Assuming biomass with a lower heat value (LHV) of 5.14 MWh per ton, 256 000 metric tons of biomass are used as fuel every year.

Dimensioning full load hours for CHP was set to 7 000 hours per year. This is somewhat higher than data from Nyström et al. (2011), which used 5 000 hours per year. CHP is usually dimensioned for supplying district heating during season, hence the low amount of full load hours. In the current study it was assumed that the plant is run in order to utilise fuel more effectively as in polygeneration.

Costs for producing electricity in the CHP plant were taken from Nyström et al. (2011). The heat was given a credit of 232 SEK/MWh_{th}. It was also assumed that the production will be given green electricity certificates with a value of 295 SEK/MWh electricity. The biomass fuel cost was set to 210 SEK/MWh LHV. The total electricity production costs when considering certificate and heat crediting were 396 SEK per MWh electricity produced (Table 10).

Table 10. Yearly fixed and operational costs for biomass-fuelled CHP

	Costs	Unit
Annual investment cost	434	SEK/MWh$_{el}$
Operation and maintenance	155	SEK/MWh$_{el}$
Fuel cost	681	SEK/MWh$_{el}$
Total operation and maintenance and fuel costs	836	SEK/MWh$_{el}$
Heat crediting	-580	SEK/MWh$_{el}$
Green certificate	-295	SEK/MWh$_{el}$
Total costs	396	SEK/MWh$_{el}$

5.3 Electrolysis and hydrogen storage

The cost of producing hydrogen in a small scale electrolysis unit was based on data in Saur (2008). Depending on currency rates and year of calculation, the cost of producing hydrogen through electrolysis ranges between 2.5-12 USD per kg H_2 according to Saur (2008). This equals 15-87 SEK per kg H_2 in 2010, excluding electricity costs (Table 11). The cost of an electrolyser unit producing 181 kg H_2 per day (the minimum hydrogen needed for producing 1 ton of NH_3) was calculated to be 34 SEK per kg H_2 or 2.3 MSEK per year.

Table 11. Costs for an electrolysis plant producing 100 and 1 000 kg H_2 per day (Saur, 2008) and the calculated costs for producing 182 kg H_2 per day

Size, installation	100	182	1 000	Unit
Ref	Saur, 2008	Calculated	Saur, 2008	
Capital cost	26	25	11	SEK/kg H_2
Fixed O&M	10	9	4	SEK/kg H_2
Total costs	36	34	15	SEK/kg H_2

There is a need to store hydrogen for buffering against uneven wind conditions. Generated electricity is fed directly into the process and it was assumed here that no surplus electricity is generated. Costs for storing hydrogen were calculated for the amounts of hydrogen needed for 5 days production of ammonia. Hydrogen was assumed to be stored aboveground, compressed at 350 bar pressure.

The cost for hydrogen storage is a function of amount of hydrogen stored and time of storage. These costs were calculated using data from Amos (1998) and varied between 6.6-15.6 SEK per kg H_2 stored.

For large-scale hydrogen production, data from data from Hulteberg and Karlsson (2009) was used. A cost of 7 SEK per kg H_2 for large-scale electrolysis excluding electricity costs was calculated from Hulteberg and Karlsson (2009) for a plant producing 15 000 ton H_2 per year. This also excludes contingency and contracting costs. According to data from Hulteberg and Karlsson (2009) the hydrogen production cost would be roughly 10 SEK/kg H_2 if contingency and contracting costs were included and around 40 SEK/kg H_2 if the electricity cost also was included. The calculation was assumed valid for our modelled unit producing 38 ton hydrogen per day, this being the minimum amount of hydrogen required in order to produce ammonia sufficient for the requirements of the large-scale scenario.

5.4 Ammonia production and storage

The ammonia produced was assumed to be anhydrous ammonia stored in pressurised tanks while waiting for utilisation, either for producing nitric acid or for direct use in AN production. Using data from UNIDO (1983), ammonia production from natural gas for western European data was calculated for three plant sizes (Table 12). Included in the investment costs are: materials, utilities, labour, overhead, depreciation, maintenance, insurance and taxes. The data in UNIDO (1983) does not seem to include site preparation.

Together with data for scale-up costs, estimates and US inflation indexes, the costs for small-scale ammonia production were estimated (Gerrard, 2000; Remer et al., 2008):

Small-scale: New plant size, S	1 ton per day
Large-scale: New plant size, S	208 ton per day
Scale factor, n	0.65

The costs for a small-scale ammonia production plant with capacity of 1 ton per day can vary between 3.6 and 4.9 MSEK per year, averaging 4.1 MSEK per year. The cost of producing ammonia is 9 800-13 500 SEK per ton NH_3, with an average production cost of 11 400 SEK per ton NH_3.

The costs for a large-scale ammonia production plant with capacity of 208 ton per day can vary between 125 and 158 MSEK per year, with average costs of 133 MSEK per year.

The investment cost for producing ammonia is between 1 500 and 2 100 SEK per ton NH_3, with an average cost of 1 750 SEK per ton NH_3 produced.

Table 12. Calculated ammonia plant investment cost (C) at scale factor n = 0.65 and initial plant size S_r (ton/day)

Original plant size (S_r)	150	250	1 000	
Original investment cost in 1983 (C_r)	6.0	7.8	26	MUSD
Small-scale				
Scaled investment cost (C) in 1983	0.25	0.23	0.31	MUSD
Scaled investment cost (C) in 2010	3.9	3.6	4.9	MSEK
Large-scale				
Original investment cost in 1983 (C_r)	6.0	7.8	26	MUSD
Scaled investment cost (C) in 1983	7.9	7.3	10	MUSD
Scaled investment cost (C) in 2010	125	116	158	MSEK

5.5 Nitric acid production

Western European data from UNIDO (1983) were used to calculate the costs for small-scale nitric acid production. Together with data for scale-up costs, estimates and inflation indexes, the costs for small-scale ammonia production were estimated:

Small-scale: New plant size, S	1.9 ton per day
Large-scale: New plant size, S	385 ton per day
Scale factor, n	0.65

Average costs were calculated from plants with a production capacity of 300, 500 and 1 800 ton per day. Calculated annual average costs for small-scale production were 2.4 million SEK per year and for large-scale production 76 million SEK per year.

Table 13. Calculated nitric acid plant investment cost (C) at scale factor n = 0.65 and initial plant size S_r (ton/ day)

Original plant size (S_r)	300	500	1 800	
Original investment cost in 1983 (C_r)	2.7	4.4	17	MUSD
Small-scale				
Scaled investment cost (C) in 1983	0.11	0.13	0.21	MUSD
Scaled investment cost (C) in 2010	1.8	2.1	3.2	MSEK
Large-scale				
Original investment cost in 1983 (C_r)	2.7	4.4	17	MUSD
Scaled investment cost (C) in 1983	3.6	4.2	6.6	MUSD
Scaled investment cost(C) in 2010	57	66	104	MSEK

5.6 Mineral fertiliser plant

When calculating costs for mineral fertiliser, plant data from UNIDO (1983) for AN production from natural gas in western European data were used. Together with data for scale-up costs, estimates and inflation indexes, the costs for small-scale ammonia production were estimated.

- Small-scale: New plant size, S 2.5 ton per day
- Large-scale: New plant size, S 510 ton per day
- Scale factor, n 0.65

Average costs were calculated from plants with a production capacity of 355, 591 and 2 364 ton per day. Calculated annual costs for small-scale production were 2.2 million SEK per year. The cost for large-scale AN production varied between 61 and 84 million SEK per year. The average cost was calculated to be 71 million SEK per year.

Table 14. Calculated mineral fertiliser plant investment cost (C) at scale factor n = 0.65 and initial plant size S_r (tons/day)

Original plant size (S_r)	365	590	2 364	
Original investment cost in 1983 (C_r)	2.8	4.5	14	MUSD
Small-scale				
Scaled investment cost (C) in 1983	0.12	0.14	0.17	MUSD
Scaled investment cost (C) in 2010	1.9	2.2	2.6	MSEK
Large-scale				
Scaled investment cost (C) in 1983	2.8	4.5	13.6	MUSD
Scaled investment cost(C) in 2010	61	69	84	MSEK

6 RESULTS

6.1 Plant inputs and outputs

The calculated inputs and outputs to the production plants in the different scenarios are presented in Table 15. The N gross output is the amount of nitrogen that each plant produces, while the N net output is the output after deduction of the internal requirements of the biomass plantations.

Table 15. Inputs and outputs to production plants per day. Gross output is the output from the production gate, net output is that after a certain amount of nitrogen has been returned to the biomass plantation

Scenario	1 Small-scale wind	2 Large-scale wind	3 (Straw) Large-scale CHP	3 (Salix) Large-scale CHP	4 (Forest res) Integr. Large-scale CHP	5 (Straw) Therm. gasification	5 (Salix) Therm. gasification	
Biomass input			17 360	17 444	17 453	6 687	6 687	GJ/day
Wind power use	40	4540						GJ/day
N gross output	1	165	170	171	171	167	167	ton/day
N net output	1	165	165	165	165	165	165	ton/day
Electr. surplus						154	153	GJ/day
Heat surplus	3	1 795	12 964	11 124	1 863	0	0	GJ/day

In Table 16, the same data are expressed per kg N net output.

Table 16. Inputs and outputs per kg N net output. Gross output is the output from the production gate, net output is that after a certain amount of nitrogen has been returned to the biomass plantation

Scenario	1 Small-scale wind	2 Large-scale wind	3 (Straw) Large-scale CHP	3 (Salix) Large-scale CHP	4 (Forest res) Integr. Large-scale CHP	5 (Straw) Therm. gasification	5 (Salix) Therm. gasification	
Biomass input			105	106	106	40	41	MJ/kg N net
Wind power use	49	28						MJ/kg N net
N gross output	1.00	1.00	1.03	1.04	1.04	1.01	1.01	Kg N/kg N net
N net output	1.00	1.00	1.00	1.00	1.00	1.00	1.00	Kg N
Electr. surplus						1	1	MJ/kg N net
Heat surplus	4	11	79	68	11	0	0	MJ/kg N net

6.2 Transport distance biomass

The calculated transport distance of the raw material in each scenario is presented in Table 17.

Table 17. Calculated average transport distance (km) in the different biomass scenarios

Scenario	3 (Straw) Large-scale CHP	3 (Salix) Large-scale CHP	4 (Forest res) Integr. Large-scale CHP	5 (Straw) Therm. Gasification	5 (Salix) Therm. Gasification
Average transport distance (km)	184	118	100	70	44

6.3 Land use

The land use for Salix in scenario 3 (large-scale CHP) was calculated to be 0.57 ha per ton N produced. For Salix scenario 5 (thermal gasification), the land use was calculated to be 0.22 ha per ton N. This is the actual land use without any deductions for by-products. Since the CHP scenario produces a lot of heat as a by-product, the land use is larger.

Straw and forest residues do not require land for cultivation as they are by-products of other systems. However, to produce one ton of N, straw needs to be collected from around 1.4 ha cereal cultivation in scenario 3 (large-scale CHP) and from 0.5 ha in scenario 5 (thermal gasification).

The amount of forest residues collected after final felling can vary, here we assumed 32 ton (RecAsh, 2009). Calculated per year in a 80-year rotation yields less than 400 kg per ha and year. Therefore the required land for the production of 1 ton N is around 25 ha.

6.4 Energy

In Table 18, the calculated energy use in the different scenarios is presented. The fossil primary energy input in the biomass scenarios is diesel for cultivation, drying, transport etc., while in the wind power scenarios it is manufacturing and decommissioning of the power plant.

The avoided fossil energy input is the avoided use of fossil-based nitrogen, the avoided heat (oil for district heating) due to surplus heat from the production, and avoided electricity (coal power) due to surplus electricity.

The replacement primary fossil energy is calculated in scenario 4, where the nitrogen production was assumed to be integrated into an existing forest residue CHP. The electricity used for nitrogen production then needs to be produced elsewhere; here we assumed that it is coal power that replaces the missing electricity.

In all scenarios except 4, there is a net primary fossil energy saving. This is because of the assumption that green fertilisers produced avoid the production of fossil-based fertilisers, but the missing electricity is produced with coal power with low energy efficiency. In other words, it costs more energy to replace the electricity than the energy that can be saved by replacing fossil nitrogen with forest residues.

Table 18. Energy use as primary fossil energy, MJ/kg N

Scenario	1	2	3 (Straw)	3 (Salix)	4 (Forest res)	5 (Straw)	5 (Salix)
	Small-scale wind	Large-scale wind	Large-scale CHP	Large-scale CHP	Integr. Large-scale CHP	Therm. gasification	Therm. gasification
Fossil primary energy input	2	2	3	2	2	1	1
Avoided primary fossil energy	-58	-67	-153	-138	-67	-55	-55
Replacement of reduced electricity					78		
Total	-56	-65	-150	-136	13	-54	-54

6.5 Greenhouse gas emissions

The GHG emissions per functional unit for the different scenarios are presented in Table 19. All the scenarios show a net reduction in GHG. In the scenarios using biomass, the largest differences are between different technical solutions and not between choices of raw material.

The CHP solution (scenario 3) has the largest GHG emissions reduction. This is mainly because a large amount of the incoming biomass is converted to heat, which was assumed to replace fossil fuel-based district heating. This also means that the land use per kg nitrogen is larger in the CHP scenarios, which make it even more beneficial in the Salix scenarios as the soil carbon was assumed to increase.

As explained in the previous section, the primary fossil energy use is larger than the reference system in the forest residue scenario. This is mainly due to the assumption that the missing electricity is replaced by coal power. However, the GHG emissions are reduced compared with the reference system. This is because the GHG emissions reduction is not only connected to energy use, but also to the nitrous oxide emissions from nitric acid production. In the reference system old technology was assumed, but in the renewable scenarios it was assumed that the plants were equipped with catalytic nitrous oxide removal filters. There is therefore a GHG saving in the forest residues scenario, even though the primary fossil energy use is higher.

In the thermal gasification scenarios the main product is nitrogen and only small amount of surplus electricity is sold to the grid. The replacement of fossil N-fertilisers dominates the results, so that the production only plays a minor role.

In the wind power scenarios no large differences can be seen between small- and large-scale production. This is mainly because the replacement of fossil N-fertilisers dominates the results so that the production only plays a minor role.

Table 19. Emissions of greenhouse gases expressed as kg CO_2-eq/kg N, after deduction of internal requirements in biomass scenarios

Scenario	1	2	3 (Straw)	3 (Salix)	4 (Forest res)	5 (Straw)	5 (Salix)
	Small-scale wind	Large-scale wind	Large-scale CHP	Large-scale CHP	Integr. Large-scale CHP	Therm. gasification	Therm. gasification
Biomass production and transport	--	--	0.2	0.6	0.2	0.1	0.2
Soil carbon emissions/uptake	--	--	0.8	-0.7	0.3	0.3	-0.3
Wind power production	0.7	0.5	--	--	--	--	--
Nitric acid production	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Excess heat	-0.4	-1.0	-7.1	-6.1	-1.0	0.0	0.0
Excess electricity	--	--	--	--	--	-0.2	-0.2
Reduced electricity production	--	--	--	--	4.8	--	--
Subtotal	0.8	-0.1	-5.7	-5.8	4.7	0.6	0.2
Replacement of fossil nitrogen	-7.3	-7.3	-7.3	-7.3	-7.3	-7.3	-7.3
Total	**-6.5**	**-7.4**	**-13.0**	**-13.1**	**-2.6**	**-6.7**	**-7.1**

6.6 Production costs

Estimated costs for small-scale production of AN fertilisers (scenario 1) are presented in Table 20. The highest cost is allocated to production of ammonia, nitric acid and mineral fertiliser. These plants are in general large-scale plants and the cost of small-scale production is high compared with that of existing large-scale production sites. Almost half the cost can be attributed to production of commodities and fertiliser production.

Table 20. Costs (MSEK per year and SEK per kg AN) for small-scale production of ammonium nitrate fertiliser using electricity from wind power combined with large-scale fertiliser production

	Total annual costs	Costs per kg AN	Costs per kg AN-N
Electricity generation, wind power	1.3	1.4	4.3
Hydrogen production	2.3	2.5	7.5
Hydrogen storage for 5 days production	0.5	0.6	1.7
Ammonia production	4.1	4.6	13.8
Nitric acid production	2.4	2.6	7.8
Mineral fertiliser production	2.2	2.5	7.4
Total, production costs at factory gate	**12.8**	**14.3**	**42.6**

As a reference, the selling price for fossil based nitrogen fertilisers on the market is now (2011) at around 11 SEK/kg N (ATL, 2011), se further discussion on this in chapter 8.3.

Estimated costs for large-scale production of AN fertilisers (scenario 3) are presented in Table 21. For large-scale production, the highest costs are associated with producing electricity and thereby hydrogen, as almost 90% of electricity generated is utilised during electrolysis. In all, 44% of production costs for large-scale production of AN fertiliser are in electricity and hydrogen production.

As can be seen, the hydrogen production cost was assumed much larger in the small scale scenario than in the large scale. Further, the contribution of the hydrogen production cost relative to the electricity cost is much higher in the small scale scenario. This is because of the assumptions of quite high capital cost for small scale electrolysis. This is based on Saur (2008), which state that in smaller systems the capital costs dominate the cost of hydrogen, but that mass production considerably can reduce these costs. In larger scale hydrogen production systems, the electricity cost is instead dominating.

Table 21. Costs (MSEK per year and SEK per kg AN) for large-scale production of ammonium nitrate fertiliser using electricity from CHP combined with large-scale fertiliser production. The heat credit has already been subtracted from the electricity generation figures

	Total annual costs	Costs per kg AN	Costs per kg AN-N
Electricity generation, CHP	158	0.8	2.5
Hydrogen production and storage	60	0.3	1.0
Ammonia production	133	0.7	2.1
Nitric acid production	76	0.4	1.2
Mineral fertiliser production	71	0.4	1.1
Total, production costs at factory gate	**498**	**2.7**	**8.0**

7 SENSITIVITY ANALYSIS

All modelling is associated with uncertainty. One way to examine the dynamics of a system is to test its sensitivity to changes in specific parameters or assumptions. The following sections describe a sensitivity analysis carried out for GHG emissions and costs.

7.1 Greenhouse gas emissions

7.1.1 Changing the functional unit

Choice of functional unit can have a large impact on the interpretation of the results. Cherubini (2010) recommends that LCA of dedicated crops be expressed on a per hectare basis. This was tested for the five scenarios studied and the results are presented in Table 22. It can be seen that the biomass thermal gasification scenarios gave the largest reduction in GHG. This is because in the thermal gasification scenarios, more nitrogen per hectare is produced.

Table 22. Emissions of greenhouse gases expressed as kg CO_2-eq/ha, after deduction of internal requirements in biomass scenarios

Scenario	3 (Straw) Large-scale CHP	3 (Salix) Large-scale CHP	4 (Forest res) Integr. large-scale CHP	5 (Straw) Therm. gasification	5 (Salix) Therm. gasification
Biomass production and transport	160	1 060	10	110	910
Soil carbon emissions/uptake	550	-1 230	10	550	-1230
Nitric acid production	300	730	20	760	1 860
Excess heat	-5 090	-10 650	-40	0	0
Excess electricity				-290	-720
Reduced electricity production			190		
Subtotal	-4 090	-10 090	190	1 130	820
Replacement of fossil nitrogen	-5 230	-12 730	-290	-13 600	-33 250
Total	-9 310	-22 820	-100	-12 480	-32 430

Per functional unit kg N, the model favours systems with a large land use, creating high amounts of by-products which can replace fossil alternatives. However, this is only valid as long as the by-product replaces a less good alternative. The model is also only valid when there is enough land to expand into, or straw that has no other use can be harvested.

If the functional unit were instead the use of 1 hectare, the system that produces most nitrogen per hectare would be most favourable. However, when comparing dedicated cropping systems with crop residue systems or wind power systems, it is not relevant to express the functional unit as 1 hectare. In studies examining the best utilisation of 1 hectare of land for cultivation, it could be relevant to use this unit of comparison, as the difference between choices of crops could then be better assessed.

7.1.2 *Nitrogen reference*

An important factor in the GHG calculations is the reference system, as all savings are expressed relative to this. In the base case we assumed that the bio-based nitrogen would replace natural gas-based nitrogen with emissions of 7.3 kg CO_2-eq/kg N. However, the emissions can vary depending on raw material, type of technology and age of the production plant (Table 5). In the sensitivity analysis, we tested the results of bio-based nitrogen replacing coal-based ammonia (9.7 kg CO_2-eq/kg N) and natural gas-based ammonia produced in a modern plant (2.8 kg CO_2-eq/kg N). The results are presented in Figure 12. As can be seen, scenario 4 would not give a saving, but rather a net contribution to global warming, if the bio-nitrogen replaced low emitting fossil-based nitrogen.

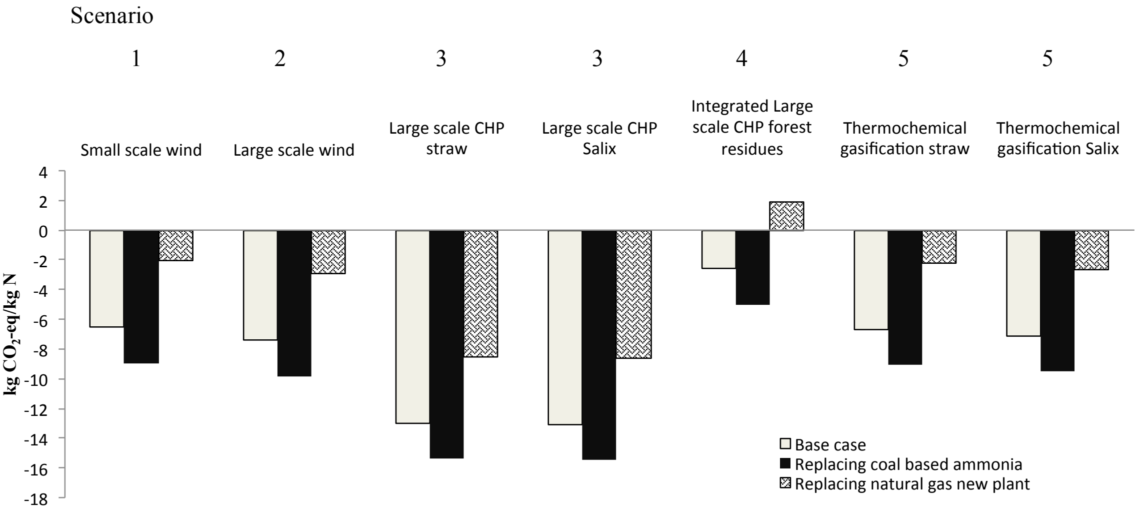


Figure 12. Sensitivity of results to choice of nitrogen reference.

7.1.3 *Heat and electricity reference*

The heat and electricity reference is also important. When producing excess heat or electricity, in the base case it was assumed that fossil energy will be pushed off the market. However, there is also a chance that the less competitive renewable energy market will be affected. The results were tested assuming that the excess energy replaces other renewables (wind power and heat based on forest residues; data collected from Uppenberg et al., 2001). As can be seen in Figure 13, this assumption has a certain influence on the results, especially for the CHP alternatives that produce large amounts of excess heat. However, there will still be a net reduction in overall GHG emissions.

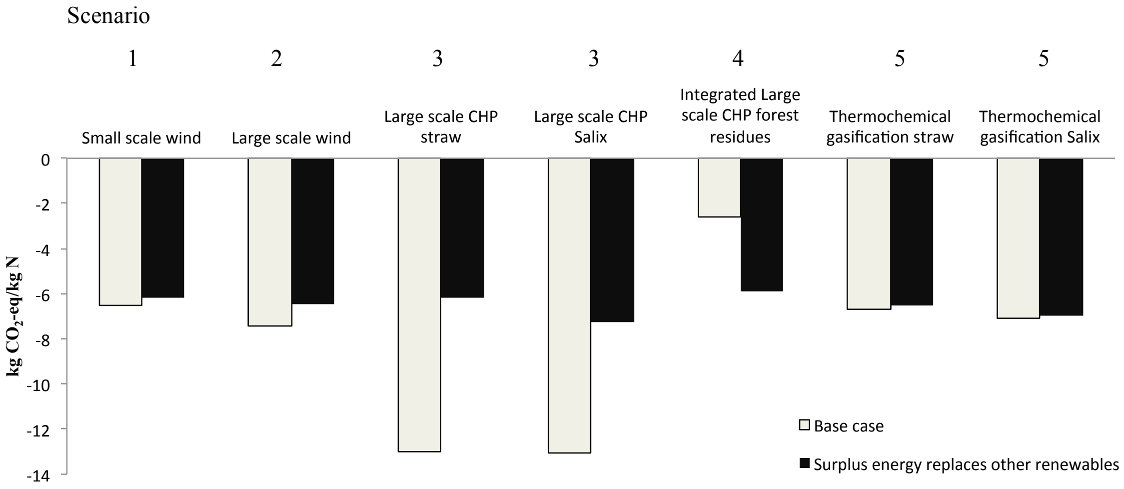


Figure 13. Sensitivity of results to assumptions on energy substitution.

7.1.4 Soil carbon changes

Another important factor is the assumption on soil carbon changes. In the base case it was assumed that harvesting straw would give a reduction of 150 kg C/ha and year. In the literature, however, the impact of straw removal varies greatly, from 385 kg C/ha and year carbon losses (Saffih-Hdadi and Mary, 2008) to having no significant impact at all (Röing et al., 2005). The results were therefore tested for the range 0-385 kg C/ha and year.

Salix was tested for values ranging between a loss of 1309 kg C/ha and year (planting on previous forest) and carbon accumulation of 1700 kg C/ha and year (planting on previous fallow land) (Börjesson, 1999). Removing forest residues can give losses of between 3 and 50 kg C/ha and year (Lindholm, 2010). The results of the soil carbon sensitivity analysis are presented in Figure 14. As can be seen, soil carbon has an influence on the global warming results, especially in the Salix CHP scenario.

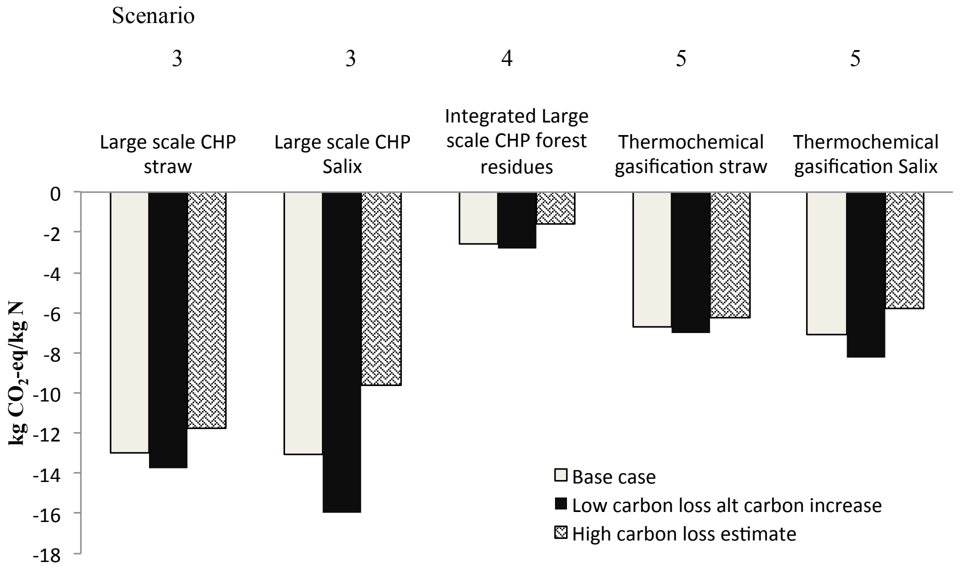


Figure 14. Sensitivity of results to assumptions on soil carbon changes.

7.1.5 Indirect land use

When using biomass for new activities, emissions associated with loss or accumulation of carbon at the site of cultivation of the raw material can occur. This can be referred to as the direct land use change and in this study was included in the base case. The assumption in the base case was that Salix plantation was placed on previously unused land and straw and forest residues collected from previously unutilised sites.

However, it is debatable whether this will actually happen. There is a possibility that Salix will be planted on fields where other activities previously took place. Those activities will then be diverted to other locations, which can lead to emissions of GHG. Even if Salix is planted on previously unused land, the plantation itself prevents any other type of land use, for example expansion of crop production, and can therefore be argued to lead to indirect land use change (iLUC).

In recent years there has been an intensive debate on the indirect land use changes connected with the production of liquid biofuels. However, quantification of the indirect land use is very difficult and usually requires use of economic equilibrium models which can predict the market response to an increased demand for biomass. It is not the case that 1 hectare of land use automatically leads to 1 hectare of land use elsewhere, since increased crop prices can lead to lower consumption or an intensification of agriculture. The models are very complex and the results are associated with high uncertainty. The figure usually varies between -50 and 100 g CO_2-eq per MJ biofuel, with extremes up to 300 g CO_2-eq per MJ (Ahlgren and Börjesson, 2011).

Here we tested the impact on the results in the Salix scenarios of assuming that the occupation of 1 hectare of land causes 1 hectare of crop cultivation elsewhere and a soil carbon loss connected to that hectare of either 10 ton C/ha (low estimate) or 95 ton C/ha, according to the variation reported by Edwards et al. (2010). The soil carbon losses were divided over 20 years. Straw and forest residues were assumed to not cause any indirect land use. The results for the Salix scenarios are presented per kg N produced (Figure 15). It is clear that including iLUC has an effect on the results, but there is still a net saving of GHG compared with using fossil-based nitrogen.

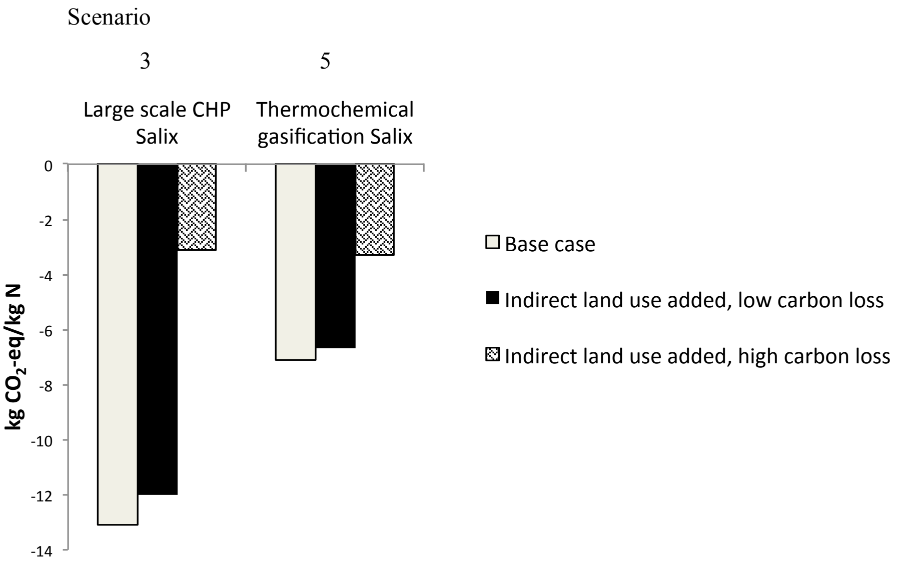


Figure 15. Changes in results when indirect land use changes are included.

7.2 Production costs

Costs for producing AN fertiliser via small-scale electrolysis or large-scale production using biomass in CHP are at best rough estimates. Even the large-scale production studied here can be considered small-scale compared with existing plants today for producing hydrogen, ammonia, nitric acid and mineral fertilisers.

Sensitivity analyses were performed for a number of parameters that were identified as affecting the results (Table 23).

Full load hours are used for dimensioning the size of wind power unit and CHP. Changing full load hours resulted in a larger or smaller unit and thereby a change in investment costs. Full load hours vary depending on geographical location of the wind power plant or how CHP is utilised. The effect on total costs from utilisation time was tested by increasing or decreasing 1 000 hours.

The investment costs for power production are highly dominant for the electricity production price. As much electricity is used in electrolysis, it can be expected that this will have an influence on the results. In the sensitivity analysis, a 50% increase or decrease in the investment costs was tested.

Re-sizing production plants for ammonia, nitric acid and fertiliser production is associated with a large number of uncertainties. The fertiliser production costs were tested by changing production costs for these commodities. Total production costs were increased or decreased by 50%.

The scale factor used when re-sizing production plants can have a major impact on production costs. The larger the difference between original plant size and new plant size, the larger the uncertainty in the results. The scale factor was decreased to 0.5 or increased to 0.8.

Table 23. Parameters changed in the sensitivity analysis for small- and large-scale scenarios

	Small-scale	Large-scale
Changing full load hours by ± 1 000 hours per year for wind power and CHP	X	X
Changing investment cost electricity production by ± 50%	X	X
Changing costs for electrolyser by ± 50%	X	X
Changing costs for ammonia production by ± 50%	X	X
Changing costs for nitric acid production by ± 50%	X	X
Changing costs for AN production by ± 50%	X	X
Decreasing scale factor to 0.5	X	X
Increasing scale factor to 0.8	X	X
Decreasing heat utilisation -50%		X

For small-scale production of AN fertilisers, the variables shown in Table 23 were changed in a sensitivity analysis. The impact on total costs for producing AN fertiliser is shown in Table 24.

Table 24. Results of cost sensitivity analysis, production of AN fertiliser

Parameter	Small-scale	Large-scale
Increase full load hours	-6%	-8%
Decrease full load hours	17%	6%
Power production investment costs	± 9%	± 17%
Electrolyser investment costs	± 9%	± 5%
Ammonia production investment costs	± 16%	± 13%
Nitric acid production investment costs	± 9%	± 8%
AN fertiliser production investment cost	± 9%	± 7%
Scale factor decreased	97%	5%
Scale factor increased	-40%	- 4%
Decreasing heat utilisation		+23%

As can be seen in Table 24, assumptions on scale factor had a large influence in the small-scale scenario. The cost for producing AN fertiliser can vary by as much as 97% compared with default values chosen for small-scale production, meaning a variation in the calculated production price between 26 and 84 SEK per kg N.

The closer the new plant size to the original plant size, the smaller the impact of choice on scale factor. Changing the scale factor in the large-scale production therefore did not have a large impact on the results.

The electricity production price (steered to a large extent by the power production investment costs) had a large influence in the large-scale scenario, but less in the small-scale scenario. This is because all other costs in the small-scale scenario are much larger, giving the electricity cost a relatively smaller influence.

How much of the heat that can be sold is also of importance in the large scale scenario which has a large surplus of heat. A reduction of half of the amount of sold heat (or a 50% reduction in price) leads to a 23% higher nitrogen cost in this study.

8 DISCUSSION

8.1 Uncertainties associated with LCA modelling

The results showed that the use of fossil energy and the emissions of GHG in most of the systems studied were lowered when green nitrogen was used instead of fossil-based nitrogen. However, these results are based on a number of assumptions concerning choice of data and system boundaries. Some of the assumptions were tested in the sensitivity analysis, which showed for example that the assumption on type of fossil nitrogen replaced is important for the results.

However, some issues are more difficult to include in the sensitivity analysis. For example, some of the scenarios studied use wind power, some use biomass from land. It is clear that this assessment on the best system (from a GHG perspective) needs to be put into context. If Sweden has a shortage of land, using biomass could lead to indirect land use changes, and then wind power is preferable. If there is no shortage of land, biomass could be the best alternative. However, the good performance in the biomass CHP scenarios compared with wind power is subject to assumptions on surplus heat replacing fossil fuels.

The choice of functional unit is also very important. In the base case results, 1 kg of nitrogen was used. In the sensitivity analysis the functional unit was changed to 1 hectare, which changed the relative GHG ranking of the biomass scenarios.

To draw comparisons even further, the functional unit should reflect the function a system provides. This means that a production process has a driver which is the reason why the company exists, the driver being a main product (the functional unit) with by-products. In this study we assumed that nitrogen fertiliser product was the key driver, and that the heat in the CHP scenarios was the by-product. However, the heat could be the main product and the nitrogen the by-product, which would change the calculations completely.

In addition, the scenarios are difficult to compare since they have different time perspectives. The technology for scenarios 2-4 already exists today on a commercial scale (i.e. all the process parts exist, although nobody has yet put these parts together), while the small-scale and thermal gasification scenarios need more time to develop.

In the present study, only energy balance and GHG emissions were assessed. The GHG emissions have lately been the dominant environmental impact in scientific studies, policy and regulation. However, many other environmental impacts can occur in a system, such as eutrophication, acidification, impacts on biodiversity and emissions of toxic compounds. These also have an impact on evaluation of the environmental sustainability of a system.

In conclusion, it is very difficult to make general recommendations on choice of technology and raw material since the optimum choice is dependent on the context. Each case must be carefully investigated and the raw material checked for its sustainability.

8.2 Best use of renewable resources

A question that arises is whether it is a good idea to use biomass for producing nitrogen at all, in order to lower anthropogenic GHG emissions, rather that using it to make heat and electricity. In a study by Gustavsson et al. (2007), a number of different scenarios for the use of biomass in Sweden were modelled (although not nitrogen fertiliser production). The highest GHG reduction was achieved by expanding the district heating system. In the present study, it was also the scenarios with large quantities of heat production that showed good GHG performance. Choice of raw material (straw or Salix) proved to be of less importance.

However, there is a risk that the surplus heat produced will replace other renewable sources, which would lower the GHG reduction (see sensitivity analysis). This risk also applies for new wind power. However, as there is no renewable nitrogen on the market, it is certain that green nitrogen will replace fossil alternatives. This is a good argument for producing green fertilisers.

Maximising the reduction in GHG emissions could be one criterion for best use of renewable resources. Food safety could be another and nitrogen is a vital component in maintaining high yields in crop production. Production of nitrogen should in other words not be regarded as competing with other uses of renewables, but as a fundamental prerequisite for continued production of food and energy for a growing world population.

8.3 Cost of production and price competitiveness

However important GHG reductions become, the price competitiveness of green nitrogen will be decisive for commercial introduction. The world market price for ammonia was 2 800 SEK per ton ammonia in November 2010 (www.icis.com). The ammonia price is related to the natural gas price, but even more to the oil price (Figure 16).

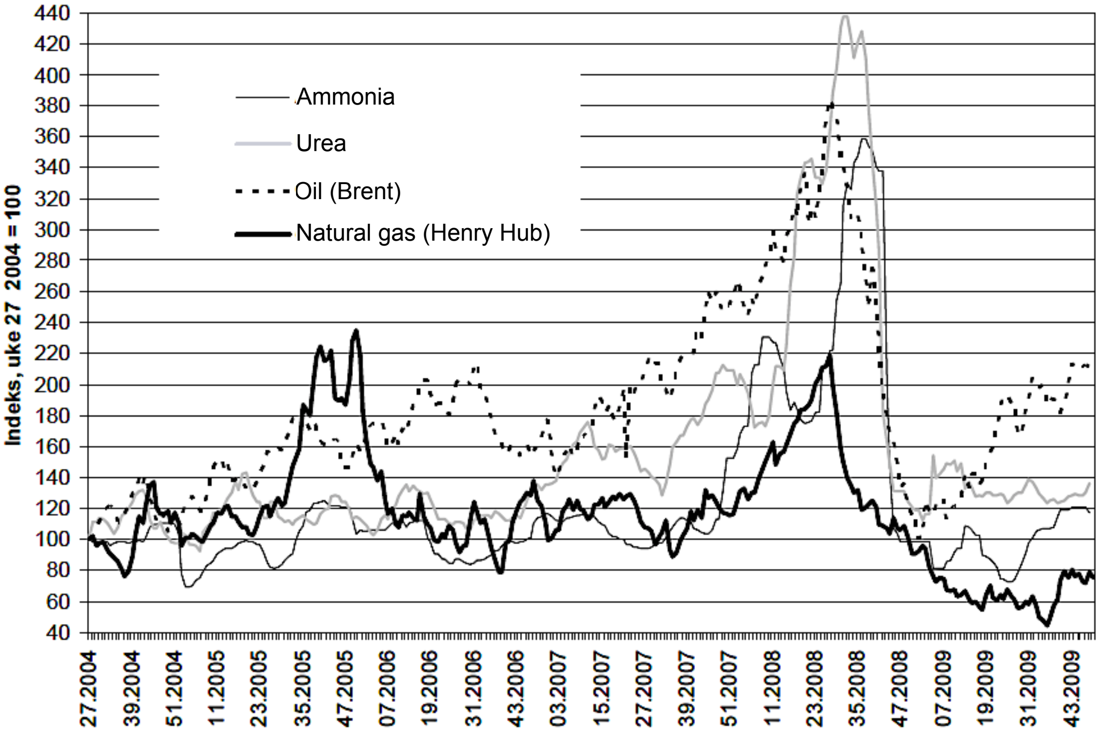


Figure 16. Indexed international price trends for urea, ammonia, natural gas and oil. Index week 27-2004=100. Period week 27/2007 – week 48/2009 (Pettersen et al., 2010).

Statistics on the price of nitrogen fertilisers on the Swedish market are scarce, but it seems to follow the ammonia price. During 2004-2007, the price of nitrogen on the Swedish market remained at a steady 8-10 SEK/kg N (statistics for the fertiliser called Axan NS 27-4). During the last months of 2007, the price rose sharply and continued to rise during 2008, reaching a maximum of 18 SEK/kg N in the last months of 2008. In 2009 the price dropped remarkably, reaching a record low of 7 SEK/kg N in November 2009. In 2010 the price went up again and is now (2011) at around 11 SEK/kg N (ATL, 2011).

Ecological fertilisers are organic fertilisers containing between 2-14% nitrogen and cost somewhere between 1 and 28 SEK per kg fertiliser (Jordbruksverket, 2011). The actual price of nitrogen is higher considering the low amount of nitrogen; depending on the type of ecological fertiliser used, the price of ecological nitrogen in fertiliser is approximately 20 SEK per kg N.

In this study, the cost of small-scale nitrogen production via wind power was an estimated 43 SEK per kg N, which is much higher than the market price for fossil-based fertilisers. However, the large-scale CHP was estimated to cost 8 SEK per kg N, i.e. well below the market price for fossil-based fertilisers. These costs are calculated costs at the factory gate. However, the production costs do not always reflect the market price. Figure 17 illustrates the natural gas price (which is the largest production cost factor for ammonia production) compared with the sales price of ammonia. At times, the margins are very large and the sales price of ammonia does not reflect the actual production costs. This makes comparison with the calculated green nitrogen production costs difficult.

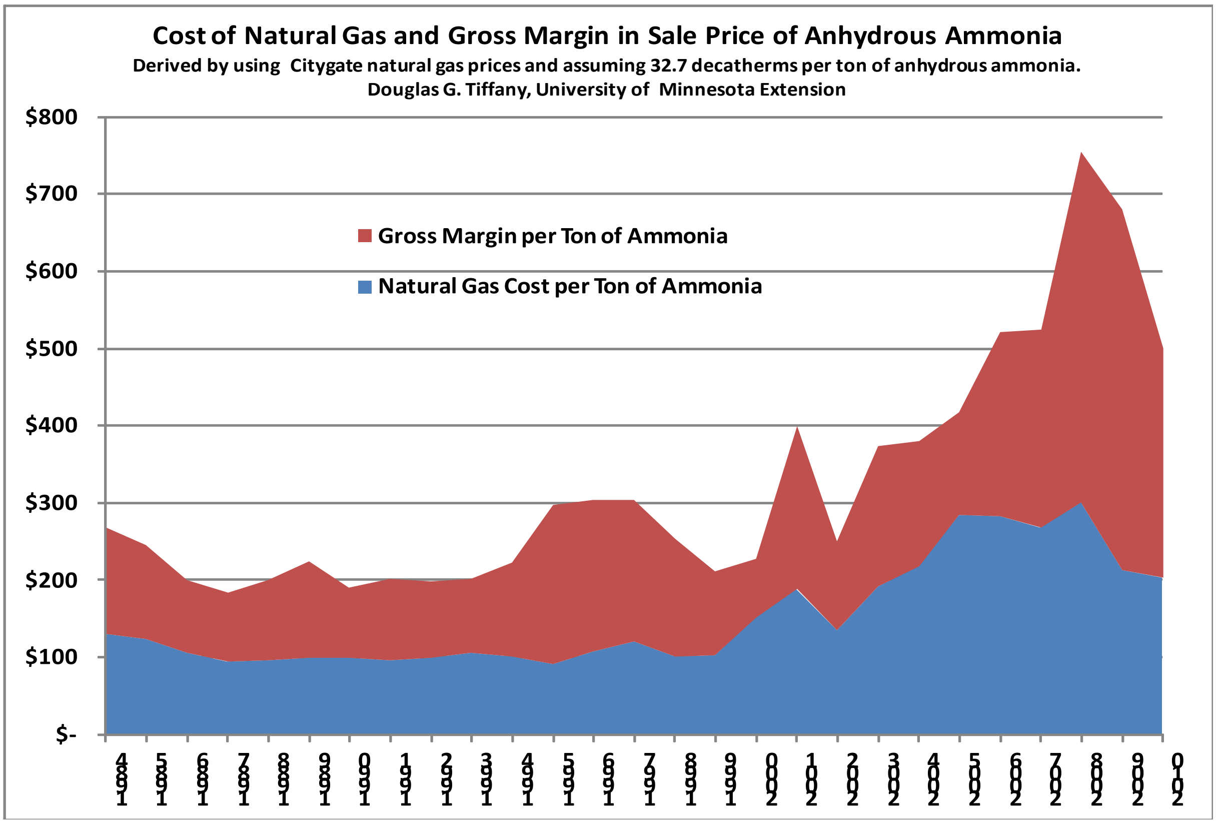
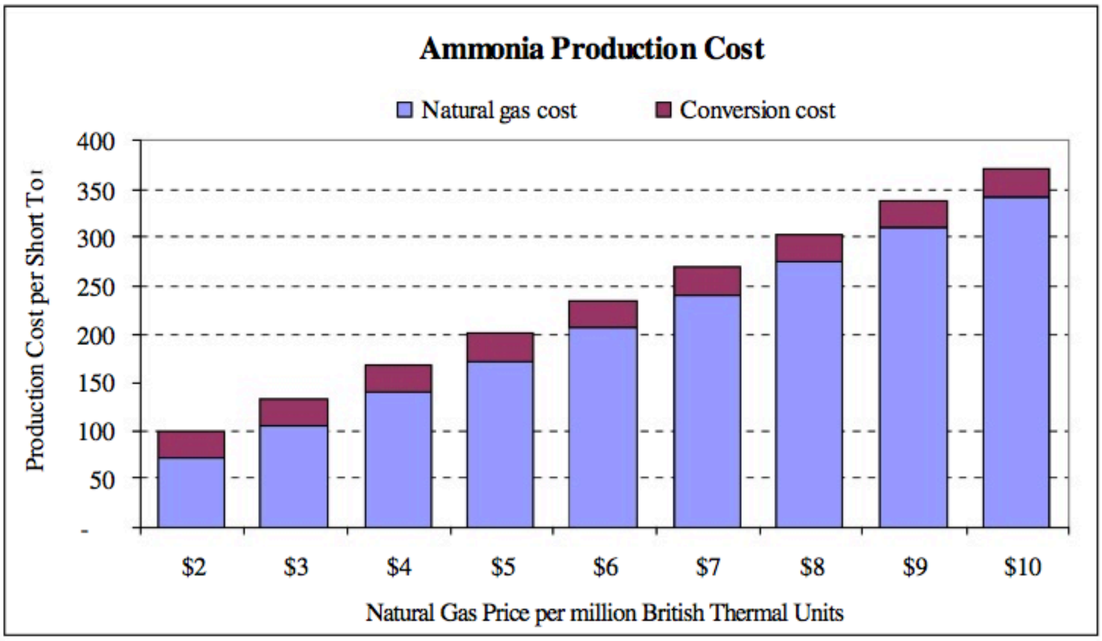


Figure 17. Contribution of natural gas costs and margins to the price of ammonia (Tiffany, 2011).

The calculated cost of green nitrogen in this study can also be compared with values reported in previous studies. An American study by Jourdan and Roguenant (1979) estimated that a small-scale (1 ton ammonia per day) plant could produce ammonia at a price of 22 SEK per kg NH_3-N (recalculated to current Swedish price level). In the present study the price for producing ammonia (i.e. skipping the following production steps to nitric acid and ammonium nitrate) was estimated to be 27 SEK per kg NH_3-N, i.e. slightly more expensive than in the study by Jourdan and Roguenant (1979).

For the large scale, we can compare the hydrogen production costs in the present study, calculated to be 49 SEK/kg hydrogen excluding electricity use. When electricity costs for producing hydrogen are included, the cost increases to 62 SEK/kg hydrogen. Using data from Hulteberg and Karlsson (2009) on electricity use, electricity price, interest rate and depreciation time, our hydrogen production cost would increase to 71 SEK/kg hydrogen excluding electricity and 100 SEK/kg hydrogen including electricity costs. For large-scale production this would mean an increase from 8 SEK/kg N to 10 SE/kg N. On the other hand, our ammonia production costs could be somewhat over-estimated. Abram and Forster (2005) suggest that with a natural gas price of $10 per BTU, feedstock makes up 90% of production costs (Figure 18).



Source: USGS: Mineral Commodity Profiles – "Nitrogen"; **Note**: Cost = production cost rather than consumer prices.

Figure 18. Production cost of ammonia divided between natural gas cost and conversion cost (Abraham and Forster 2005).

Abraham and Forster (2005) estimated the conversion cost to be around $77 per ton NH_3, equivalent to 0.8 SEK/kg NH_3-N, which can be compared with our assumption of 2.1 SEK/kg NH_3-N. However, the scale of production in our large-scale scenario was much smaller than a normal-sized fossil fuel-based ammonia plant, so higher cost could be a reasonable assumption.

As the sensitivity analysis showed, the results are associated with large uncertainties, especially in the small-scale scenario, which was highly influenced by choice of scale factor. Another uncertainty when recalculating costs for different plant sizes is the assumption that only inflation influences price changes, whereas factors such as availability of raw materials, energy and price development of commodities will probably also influence the results. Also, assumptions on the price of green electricity certificates and the amount and price of the sold excess heat play an important role in the cost assessments. Another uncertainty is the labour input in the different systems. Labour costs were included in maintenance and operation costs and treated as other O&M costs. Labour costs were based on old data both for labour requirement and cost, recalculated to today's price level, so they do not reflect technological development and automatisation.

In conclusion, small-scale production of nitrogen fertilisers based on wind was estimated to be much more expensive than the conventional and organic fertilisers that are available on the market today. On the other hand, large-scale production based on biomass combustion could be competitive. However, the results from the modelling are highly uncertain. The competitiveness of green fertilisers will also be dependent on future development of fossil fuel prices as well as possibilities for subsidies, investment support and other state driven encouragements for renewable energy, and if green fertilisers can qualify for these.

8.4 Supply Swedish agriculture with green N?

Around 167 000 tons of fossil-based nitrogen in straight and compound fertilisers are used every year in Swedish agriculture (Table 2). No nitrogen based on renewables is used in Sweden today, and introduction of that kind of production will take a number of years. Making a complete shift will take even longer. However, it is interesting to get a picture of what it would mean if all the nitrogen used today were to be supplied by renewables. In the large-scale scenarios, 165 ton per day net nitrogen was assumed to be produced. To supply Sweden with nitrogen, three such plants would be required.

For the large-scale wind power scenario, a total of around 670 MW wind power installed effect would be needed to supply Swedish agriculture with nitrogen. This can be compared against the current wind power capacity of 1600 MW (Vindstat, 2011). Wind power makes up less than 2% of total electricity production in Sweden (Energimyndigheten, 2010).

The small-scale wind scenarios require somewhat more energy for the same amount of nitrogen. Around 600 plants of the small-scale version would be needed to supply Sweden, corresponding to 1200 MW installed effect.

In the straw CHP scenario, around 5 TWh straw would be needed to produce all the green nitrogen required. In Sweden, it is estimated that 65% of the straw from cereal production is not harvested. All of it cannot be harvested, since it is needed to maintain good soil quality. The potential is further decreased due to weather and practical limitations. The straw potential taking these aspects into account is estimated to be 3-4 TWh per year (Nilsson and Bernesson, 2009).

For the Salix scenario, around 95 600 ha of plantations would be needed to supply Sweden with green nitrogen. This can be compared against the total cropped area in Sweden at present, which is 15 000 ha. However, in both these scenarios it is important to remember that not only nitrogen is produced, but also large amounts of heat that can be used for replacing fossil alternatives in the district heating net.

The forest residue scenario is a special case since it modelled integration into existing plants. Around 5 TWh per year of forest residues would be required to supply Sweden with nitrogen. The statistics on forest residue harvesting are uncertain, but it is estimated that forest residues were harvested on 32 000 ha (16% of total final felling area) in 1999, equivalent to 8.6 TWh. Forest residues is today mainly utilised in industry and district heating for heat and power production (Energiaskor, 2011). Hence, there seems to be sufficient forest residues, and the potential to increase harvesting is large.

8.5 Using green fertilisers in crop production

The emissions contributed by crop cultivation of rapeseed and winter wheat are presented in Table 25 and 26, using data from Bernesson (2004) for everything except production of nitrogen fertilisers. For rapeseed the yield was assumed to be 2 470 kg/ha (8% moisture content) and the amount of nitrogen fertiliser used 140 kg N/ha. For winter wheat the yield was 5 900 kg/ha (14% moisture content) and the amount of nitrogen fertiliser used 120 kg N/ha.

The fossil nitrogen was assumed to emit 7.3 kg CO_2-eq/kg N in production. In the renewable nitrogen options the results from Table 19 were used, but without the credit for N replacement. That is because we are now looking at another type of functional unit, namely using nitrogen fertilisers based on renewable energy compared with using fossil alternatives.

Table 25. Greenhouse gas emissions from cultivation of rapeseed when using different types of nitrogen fertilisers, g CO_2-eq/kg rapeseed

	Type of N used							
Scenario	1	2	3	3	4	5	5	
	Small-scale wind	Large-scale wind	Large-scale CHP	Large-scale CHP	Integr. large-scale CHP	Therm. gasification	Therm. gasification	Fossil
Seed	3	3	3	3	3	3	3	3
Production of P&K fertilisers	24	24	24	24	24	24	24	24
Production of N fertilisers	43	-6	-323	-347	266	34	3	413
Soil emissions	329	329	329	329	329	329	329	329
Production of pesticides	2	2	2	2	2	2	2	2
Tractive power	72	72	72	72	72	72	72	72
Heat for seed drying	30	30	30	30	30	30	30	30
Machinery inputs	2	2	2	2	2	2	2	2
Total emissions	**505**	**455**	**139**	**115**	**728**	**496**	**465**	**875**
Savings, % of fossil case	**42%**	**48%**	**84%**	**85%**	**17%**	**43%**	**46%**	**0%**

Table 26. Greenhouse gas emissions from cultivation of rapeseed when using different types of nitrogen fertilisers, g CO_2-eq/kg wheat

	Type of N used							
Scenario	1	2	3	3	4	5	5	
	Small-scale wind	Large-scale wind	Large-scale CHP	Large-scale CHP	Integr. large-scale CHP	Therm. gasification	Therm. gasification	Fossil
Seed	14	14	14	14	14	14	14	14
Production of P&K fertilisers	11	11	11	11	11	11	11	11
Production of N fertilisers	15	-2	-116	-117	96	12	4	148
Soil emissions	118	118	118	118	118	118	118	118
Production of pesticides	1	1	1	1	1	1	1	1
Tractive power	30	30	30	30	30	30	30	30
Heat for seed drying	31	31	31	31	31	31	31	31
Machinery inputs	1	1	1	1	1	1	1	1
Total emissions	**222**	**204**	**90**	**89**	**302**	**219**	**210**	**354**
Savings, % of fossil case	**37%**	**42%**	**75%**	**75%**	**15%**	**38%**	**41%**	**0%**

As can be seen, emissions of GHG can be lowered to a large extent in the cultivation of rapeseed and wheat when using the nitrogen based on renewables.

8.6 Effects on biofuel energy balance and GHG emissions

Using crops produced with green nitrogen can also have a positive impact on the energy and GHG balance of biofuel production. Tables 26 and 27 show the energy balance for rapeseed biodiesel (RME) and wheat ethanol, respectively, using different types of nitrogen fertilisers in crop production. The energy balance is calculated as the energy output divided by the energy input and thus a high value is desirable. Data for nitrogen production were taken from the previously described scenarios and data for crop and biofuel production from Bernesson (2004). The energy inputs for biofuel and by-products from biofuel production were allocated based on lower heating value.

It can be seen that the energy input for cultivation is greatly reduced for both rapeseed and wheat cultivation when using green nitrogen. For RME the energy balance also becomes much better (Table 27). For ethanol the impact of green nitrogen is not as great, since the other energy inputs, such as chemicals to the process, dominate the energy balance (Table 28).

Table 27. Energy balance for rapeseed biodiesel (RME) when different types of nitrogen fertilisers are used in rapeseed cultivation, MJ/ha

	Type of N used							
Scenario	1	2	3	3	4	5	5	
	Small-scale wind	Large-scale wind	Large-scale CHP	Large-scale CHP	Integr. large-scale CHP	Therm. gasification	Therm. gasification	Fossil
Energy inputs								
Cultivation	4865	4743	3961	3950	5417	4843	4784	11717
Process energy	3000	3000	3000	3000	3000	3000	3000	3000
Chemicals etc. for the process	2508	2508	2508	2508	2508	2508	2508	2508
Prod. of machinery and buildings	91	91	91	91	91	91	91	91
Sum of energy inputs	10464	10342	9560	9549	11016	10442	10383	17316
Sum of energy inputs, allocated to RME	6737	6658	6155	6148	7092	6723	6685	11148
Energy in RME	40343	40343	40343	40343	40343	40343	40343	40343
Balance (Out/In)	**6.0**	**6.1**	**6.6**	**6.6**	**5.7**	**6.0**	**6.0**	**3.6**

Table 28. Energy balance for ethanol when different types of nitrogen fertilisers are used in wheat cultivation, MJ/ha

	Type of N used							
Scenario	1	2	3	3	4	5	5	
	Small-scale wind	Large-scale wind	Large-scale CHP	Large-scale CHP	Integr. large-scale CHP	Therm. gasification	Therm. gasification	Fossil
Energy inputs								
Cultivation	6958	6853	6183	6174	7431	6939	6888	12831
Process energy	3777	3777	3777	3777	3777	3777	3777	3777
Chemicals etc. for the process	11780	11780	11780	11780	11780	11780	11780	11780
Prod. of machinery and buildings	118	118	118	118	118	118	118	118
Sum of energy inputs	22632	22528	21858	21849	23106	22614	22563	28506
Sum of energy inputs, allocated to ethanol	13761	13697	13290	13284	14048	13749	13718	17331
Energy in ethanol	52062	52062	52062	52062	52062	52062	52062	52062
Balance (Out/In)	**3.8**	**3.8**	**3.9**	**3.9**	**3.7**	**3.8**	**3.8**	**3.0**

The GHG profile of biofuels will also improve if green fertilisers are used in raw material production, see Figure 19 and 20. Physical allocation was used to divide emissions over biofuels and by-products, all data (except nitrogen production) is taken from Bernesson (2004).Data in Figure 20 is for ethanol production for use in diesel engines, therefore a fossil fuel ignition improver is added which gives fossil CO_2 emissions from tailpipe (black bars).

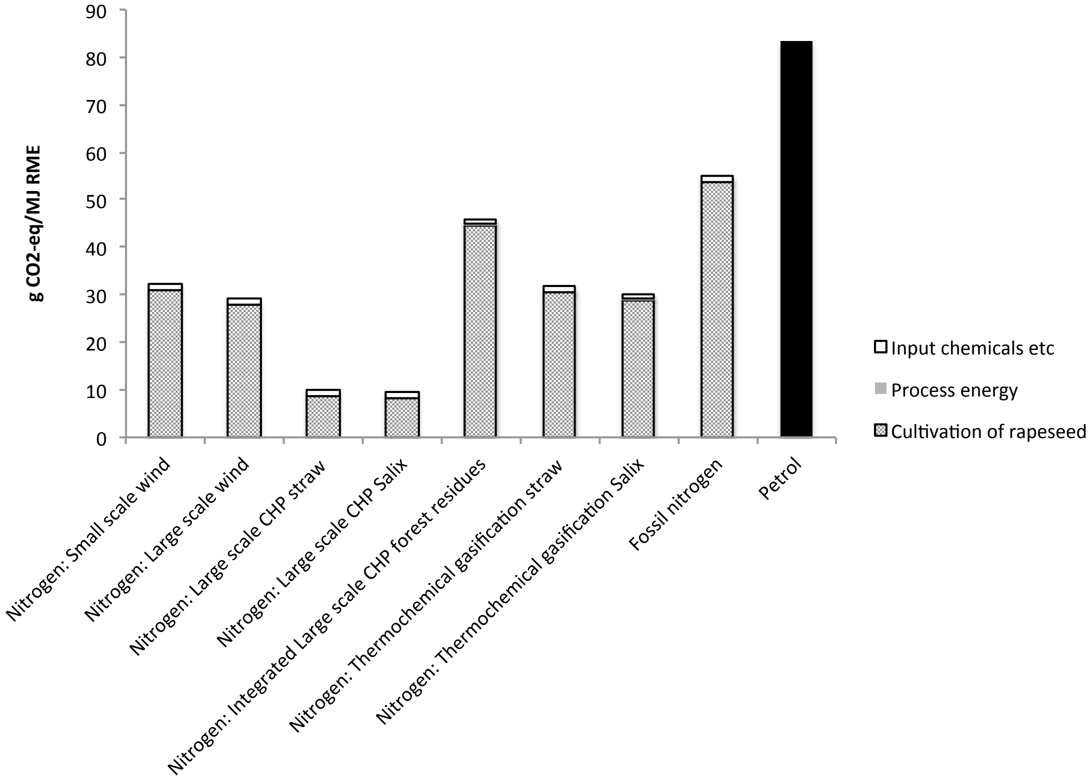


Figure 19. Greenhouse gas emissions from RME production, using different types of nitrogen fertilisers in raw material (rapeseed) cultivation. Also emissions for petrol is presented, here values from the EU renewable energy directive was used (EC, 2009).

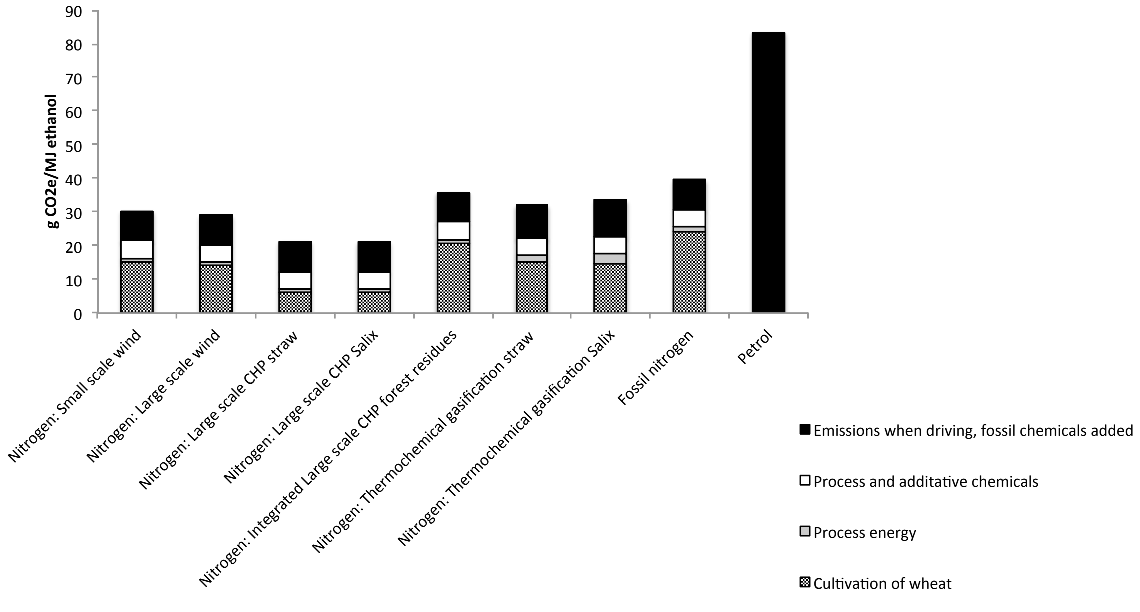


Figure 20. Greenhouse gas emissions from ethanol production and use, using different types of nitrogen fertilisers in raw material (wheat) cultivation. Also emissions for petrol is presented, here values from the EU renewable energy directive was used (EC, 2009).

9 CONCLUSIONS

The production of mineral nitrogen is one of the largest fossil energy inputs in Swedish agriculture. However, mineral nitrogen can be produced based on renewable energy. This would lower the dependence on fossil energy in food production.

This study investigated a number of viable technical production routes, including both small- and large-scale production and energy input from wind and biomass. The construction of new plants and integration within existing biomass heat and power production were also compared. For many of the scenarios studied, all the components in the technology are already available on a commercial scale and simply need to be combined into a production process.

The cost of nitrogen fertiliser production based on small-scale wind power was estimated to be 43 SEK/kg N. The cost for large-scale production based on biomass combustion was estimated to be 8 SEK/kg N, which is very competitive compared with the fossil alternatives on the market today (current cost ~11 SEK/kg N). However, the cost estimations given are very rough and associated with large uncertainties. More detailed economic modelling and calculations are needed to support any future investment decisions.

Greenhouse gas emissions were modelled using life cycle assessment methodology. The results showed that in most of the scenarios studied, GHG emissions and use of fossil energy can be significantly lowered compared with fossil-based fertilisers. The exception was integration of nitrogen production into existing biomass fired heat and power plant, since the reduced electricity output was assumed to be compensated for by marginal coal power.

Using green nitrogen in crop production can substantially lower the energy and carbon footprint of crops. Using these crops for production of biofuels can also lower the carbon footprint of the biofuels, making the comparison to fossil fuels more favourable for biofuels.

In conclusion, GHG emissions and fossil energy use can be lowered and there seem to be no technological or economic obstacles to producing green nitrogen. The resources of renewable energy on this planet are of course limited. However, green nitrogen for agriculture should be regarded as a high-priority issue, as nitrogen is one of the pillars for food and bioenergy security of supply.

It is however very difficult to make general recommendations on actual choice of technology and raw material for production of green nitrogen, since this is dependent on the context. Each case much be carefully investigated and the raw material checked for its sustainability.

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APPENDIX A. TECHNICAL DESCRIPTION OF ELECTROLYSIS SCENARIOS

Four different scenarios using electrolysis to produce the required hydrogen were studied. Scenario 1 investigated small-scale, wind power-based electrolysis, scenario 2 large-scale, wind power-based electrolysis, scenarios 3 and 4 large-scale combustion of biomass to produce electricity for the electrolysis process. Electrolysis is the process by which water is split into oxygen and hydrogen (Figure A1).

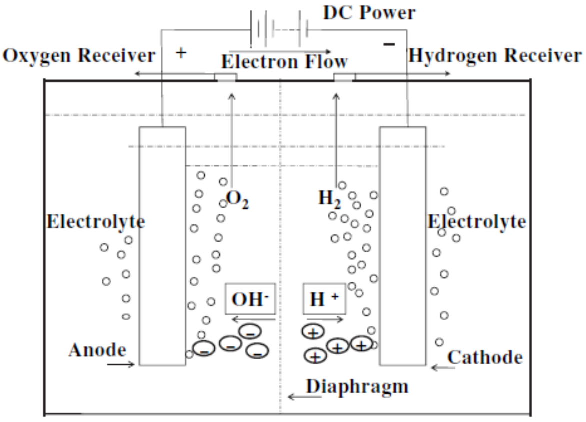

Figure A1. Basic water electrolysis system (Zeng and Zhang, 2010).

A typical ammonia plant based on natural gas produces 1000-1500 ton/day and ammonium nitrate plants generally produce from a few hundred up to 3600 ton/day. The production scale in the renewable scenarios was assumed to be much smaller. In scenario 1, 1 ton per day was assumed to be produced, as this is the scale that the wind-to-ammonia plant in Minnesota will have (see section 2.6). In scenarios 2, 3 and 4, between 165-171 ton N per day of ammonium nitrate was assumed to be produced (about 200 ton NH_3 per day).

A1. Small-scale wind power electrolysis (scenario 1)

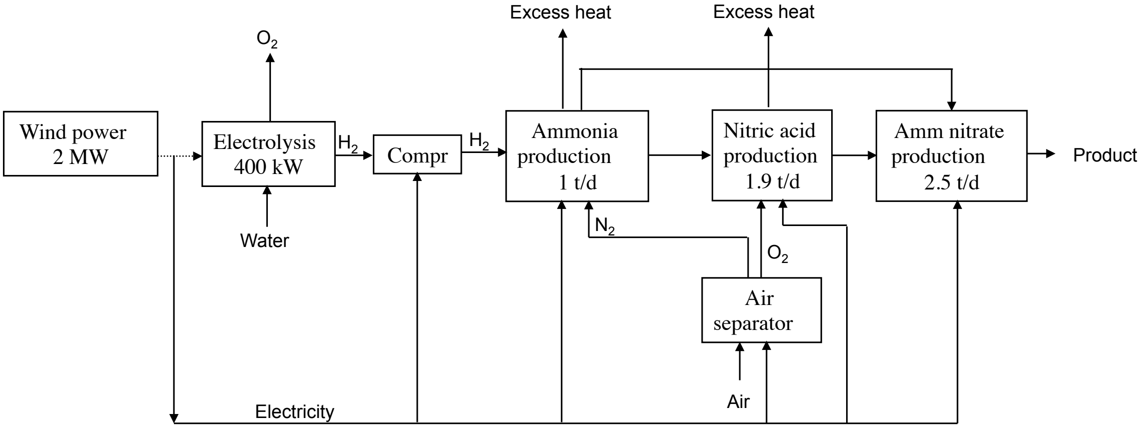

Figure A2. Scenario 1, small-scale wind to nitrogen fertiliser production

The wind power unit was dimensioned to supply the electrolysis, air separator, production and storage of hydrogen, ammonia, nitric acid and production of AN fertiliser. The size of the wind power unit depends on wind conditions and need for electricity. Accumulated daily electricity need was 11.2 MWh. Utilisation time, hours per year when the plant is assumed to work at full load, is defined as planned yearly production divided by output capacity (Hansson et al., 2007). According to Hansson et al. (2007), the full load hours in Sweden for a smaller land-based wind power unit is on average 2 150 hours per year at 100% utilisation. Land-based wind power is used 98% of time, which equals 2 107 hours per year. Assuming 2000 hours per year in this case, the wind power unit was dimensioned to 2 MW in order to supply the fertiliser production with sufficient electricity.

The electrolysis unit was assumed to be alkaline low temperature (80 °C), the electricity set to 180 MJ per kg as described in Zeng and Zhang (2010). The air separation was assumed to be done with pressure swing adsorption and a Deoxo unit, using data taken from Tifac (2011) and Vaayu Tech Engineering (2011). Data for hydrogen compression were taken from Hulteberg and Karlsson (2009).

For the ammonia synthesis, it was assumed that 5.51 kg NH_3 could be produced for every kg input of hydrogen, which is 97% of the stoichiometric value. A small reaction vessel could probably be built with thicker walls and work with higher pressure. This would require more work for pressure, but give higher yield of NH_3. On the other hand, a small plant would perhaps have more stoppages (it will most likely not be reasonable to have 24-hour staffing, meaning that if something goes wrong during night-time the plant will automatically shut down), lowering the annual production.

According to Dybkjær (2005), 162 MJ electricity is needed in the ammonia process for drivers (large-scale); this was assumed to be valid for small-scale as well. Data for nitric acid and ammonium nitrate production were taken from EFMA (2000), IPPC (2007) and Saigne (1993) due to lack of data, assuming data for large-scale are valid for small-scale.

A small-scale facility cannot invest in turbines and therefore cannot fully utilise the high pressure steam formed in different parts of the process. Instead pumps, compressors etc. must be driven by electricity (UNIDO/IFDC, 1998; Noelker, 2010). According to assumptions in UNIDO/IFDC (1998), 5.7 MJ electricity/kg NH_3 is needed for air separation, compression and ammonia synthesis loop in a small-scale electrolysis-ammonia plant. Our calculations resulted in 3.3 MJ/kg NH_3 for the same processes, slightly lower than in the UNIDO report.

A2. Large-scale wind power electrolysis (scenario 2)

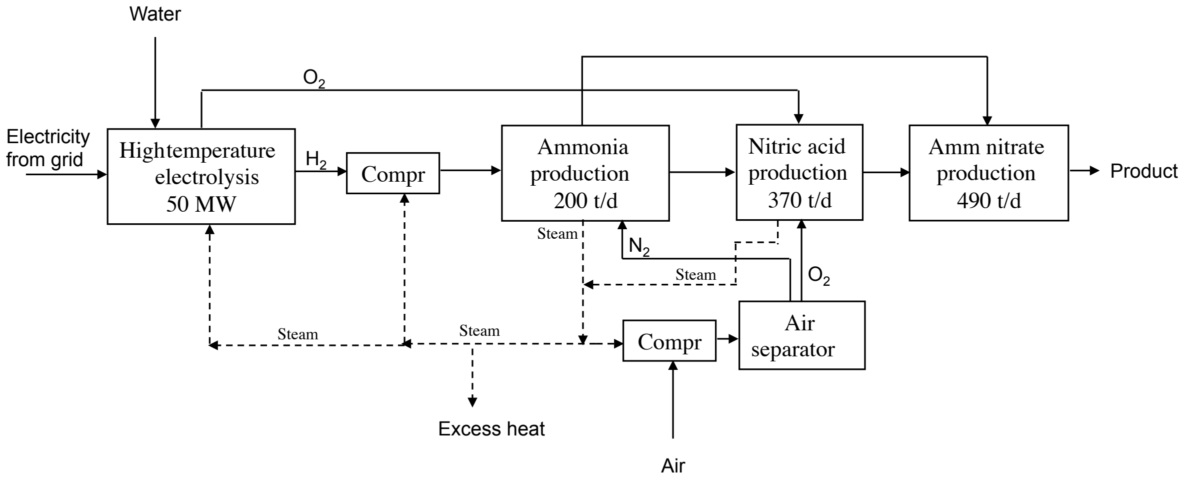

Figure A3. Scenario 2. Large-scale fertiliser production based on renewable resources. Electricity from wind power produced elsewhere, supplied via grid. Dotted lines represent steam flows.

In scenario 2, large-scale production of ammonia was studied. Large-scale production gives opportunities to utilise steam in a better way than in smaller applications. We assumed here that the plant will use steam turbines and centrifugal compressors.

Wind power bought from the grid is used to drive a solid oxide high temp steam electrolyser. Data for electrolyser were taken from Zeng and Zhang (2010) assuming energy need as electricity (120 MJ/kg H_2) and steam (28 MJ/kg H_2). The modelled electrolysis equipment is large-scale compared with existing available electrolysis equipment available on the market at present. Upscaling the electrolysis section should not be a technical problem as such; the process can be built up in modules with the same total efficiency (Hulteberg, 2010).

The hydrogen was assumed to be compressed to 200 bars before entering the ammonia synthesis. The required nitrogen was assumed to be produced in a cryogenic air separation module with input data was taken from Cornelissen and Hirs (1998). For the ammonia synthesis it was assumed that 5.51 kg NH_3 could be produced for every kg input of hydrogen, which is 97% of the stoichiometric value. Based on Dybkjær (2005), 162 MJ electricity was modelled to be used in the ammonia process for drivers. The amount of steam produced in the ammonia synthesis was based on data reported in Uhde (2011). Data for nitric acid and ammonium nitrate production were taken from EFMA (2000), IPPC (2007) and Saigne (1993).

A3. Large-scale biomass combustion and electrolysis (scenarios 3 and 4)

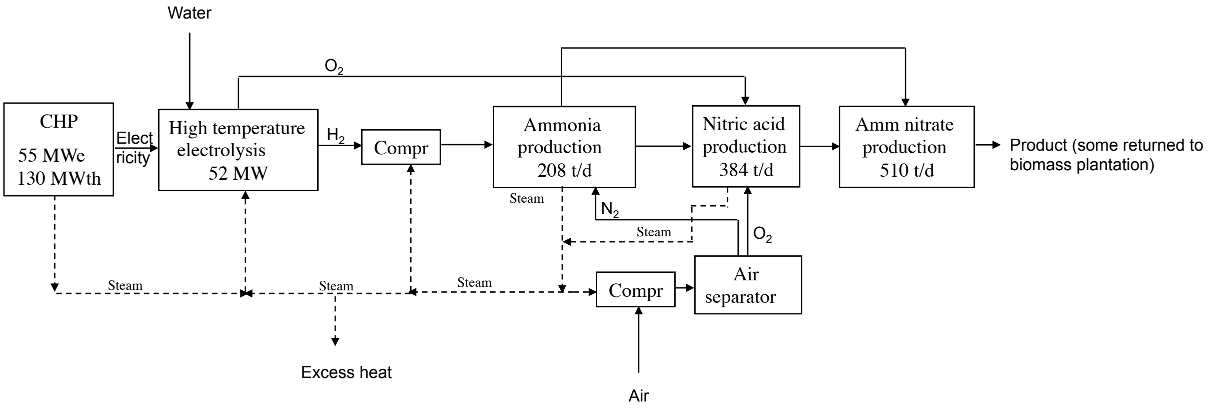

Figure A4. Scenario 3 and 4. Large-scale fertiliser production based on renewable resources. Combustion of biomass supplies the process with electricity and heat. Dotted lines represent steam flows.

In scenarios 3 and 4, production of nitrogen is done in conjunction with a biomass-fired CHP plant. A difficulty lies in matching the large size fertiliser production equipment with the restrictions of a plant with biomass feedstock due to practical and economic logistical restriction of the biomass. In Sweden the total use of wood fuel for CHP production is around 24 TWh and for energy crops 92 GWh per year. There are a handful of biomass CHP production sites using about 1000 GWh biomass fuel each per year in Sweden, and one large plant (Igelstaverket) using about 2100 GWh wood fuel per year.

In scenarios 3 and 4 we modelled a plant using approx. 1600 GWh per year incoming biomass (4.8 GWh per day), which is in line with a large-scale plant in Sweden today. The electricity produced (1.3 GWh per day) is enough to manufacture 208 ton per day ammonia, which is small in ammonia terms, but achievable without compromising with efficiency of the ammonia production (Noelker, 2010). The CHP also produces heat, 3.1 GWh per day.

As in scenario 2, the modelled electrolysis equipment is large-scale compared with existing electrolysis equipment available on the market at present. Upscaling the electrolysis section is not a technical problem since the process can be built up in modules with the same total efficiency (Hulteberg, 2010). The rest of the production chain (ammonia, nitric acid and ammonium nitrate production) was assumed to be similar to that in scenario 2.

A4. Summary of scenarios

Table A1. Input dimensions for scenarios 1-4. Assumed efficiency 0.6 for steam turbine + centrifugal compressors

Scenario	1	2	3	4	
	Small-scale wind	Large-scale wind	Large-scale CHP (Salix)	Integr. large-scale CHP (Forest res.)	
Electrolyser					
Electricity requirement	10 063	1 209 921	1 255 293	1 255 894	kWh/ day
Steam use		282 315	292 902	293 042	kWh/ day
H_2 produced	0.182	36	38	38	tons/ day
O_2 produced	1.45	290	301	301	tons/ day
Hydrogen compression					
Electricity use	515				kWh/ day
Steam use		33 609	34 869	34 886	kWh/ day
Air separation					
N_2 produced	0.848	109	113	113	tons/ day
Electricity use	348				kWh/ day
Steam use		46 279	48 015	48 038	kWh/ day
Ammonia production					
Ammonia produced	1.00	200	208	208	tons/ day
Steam produced		191 828	199 021	199 117	kWh/ day
Electricity use	45	9 000	9 338	9 342	kWh/ day
Nitric acid production					
Nitric acid produced	1.85	370	384	385	tons/ day
Steam produced		668 873	693 956	694 288	kWh/ day
Electricity use	149	29 842	30 961	30 976	kWh/ day
AN fertiliser production					
AN produced	2.46	491	510	510	tons/ day
Electricity use	61	12 282	12 742	12 748	kWh/ day

APPENDIX B. TECHNICAL DESCRIPTION OF THERMAL GASIFICATION

In scenario 5, the hydrogen needed for ammonia synthesis is produced by thermochemical gasification of biomass, and the nitrogen is extracted from normal air.

In a thermochemical gasification process, the flow of oxidation medium (usually air, oxygen or steam) is restricted. Instead of producing heat as in a combustion process, the main product is an energy-rich gas. Depending on the oxidation material and the configuration of the gasifier, the gas consists of a mixture of carbon monoxide, hydrogen, methane and carbon dioxide (McKendry, 2002). The gas also contains a number of unwanted substances such as particles, tar, nitrogen compounds, sulphur compounds and alkali compounds, which have to be removed. After cleaning, the gas is upgraded in a steam reforming and shift conversion step in order to increase the yield of hydrogen.

The hydrogen can be separated to high purity by several different technologies. In this study data were taken from Hamelinck and Faaij (2002) assuming the use of pressure swing adsorption for hydrogen separation. The yield of hydrogen was set to 0.65 MJ MJ^{-1} dry biomass (LHV) (Hamelinck and Faaij, 2002). In the gasification process, oxygen is needed. This is supplied by an air separation unit, which also supplies the ammonia synthesis with nitrogen. The power needed for the air separation (1.07 MJ per kg N produced) and for other utilities in the gasification (2.92 MJ per kg N produced) is generated internally from surplus steam from the ammonia and nitric acid production and from expansion of flue gas from the gasification. The rest of the production chain to ammonium nitrate via nitric acid is the same as for the other scenarios.

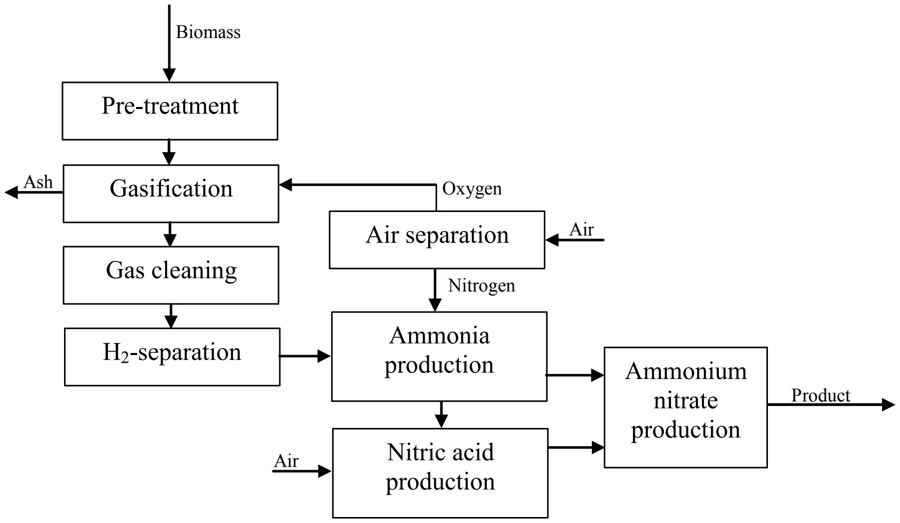

Figure B1. Flow-chart of ammonium nitrate production with biomass as feedstock.

SLU
Institutionen för energi och teknik
Box 7032
750 07 UPPSALA
Tel. 018-67 10 00
pdf.fil: http://www.slu.se/energiochteknik

SLU
Department of Energy and Technology
Box 7032
S-750 07 UPPSALA
SWEDEN
Phone +46 18 671000