

Research Paper

Consequential Life Cycle Assessment of Nitrogen Fertilisers Based on Biomass – a Swedish perspective

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Abstract: The production of mineral nitrogen represents a large fossil energy input in Swedish agriculture. However, mineral nitrogen can be produced in the Haber-Bosch synthesis, with input from renewable energy. This could lower the dependency on fossil energy and the emissions of greenhouse gases in agricultural production. The aim of this study was to investigate the land use, energy use and greenhouse gas emissions from the production of ammonium nitrate based on biomass, using consequential life cycle assessment methodology. Three scenarios are studied. In one scenario the Haber-Bosch synthesis is integrated in an existing forest residue fired combined heat and power plant. In another two scenarios thermochemical gasification of biomass in combination with Haber-Bosch synthesis is studied, using either straw or short rotation coppice (*Salix*) as raw material. The results showed that the greenhouse gas emissions and use of fossil energy can be significantly lowered. The size of emission reductions compared to using fossil fuels as raw material is dependent on choice of data, but also choice of functional unit and if e.g. indirect land use change is included. The study also showed that using green nitrogen in rapeseed production substantially can lower the carbon footprint. Further, we argue that production of nitrogen based on renewables should be a high-priority activity, as nitrogen is one of the pillars for a secure food and bioenergy supply for a growing world population.

Keywords: nitrogen; fertilisers; renewable; biomass; electrolysis; gasification; GHG; LCA; land use

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 [1]. The use of nitrogen fertilisers is predicted to increase in the future due to population growth, increased consumption of meat and increased use of biofuels [2, 3].

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 [4]. Production is most commonly based on natural gas, but gasification of coal and heavy oil also occurs. In the long run, this is not a sustainable solution for our food production, as fossil fuels is a finite energy source. The use of fossil fuels also contributes to global warming.

The total use of energy in Swedish agriculture is estimated to be 33 PJ per year; of this nitrogen production is ca 6.5 PJ [5]. The greenhouse gas (GHG) emissions due to the production of fertilisers accounts for 9% of the emissions from agriculture in Sweden [6]. On a global scale, the production of nitrogen fertilisers is calculated to represent about 1% of anthropogenic GHG emissions [4]. On a product level, the production of nitrogen fertilisers can have a large impact, e.g. when calculating the carbon footprint of food and biofuel. For example in a study by Börjesson and Tufvesson [7], nitrogen fertilisers were found to be between 3-26% of the total GHG emissions from wheat based ethanol production. For rapeseed biodiesel, the nitrogen fertiliser production was up to 29% of the GHG emissions.

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: $\text{N}_2 + 3\text{H}_2 \rightarrow 2 \text{NH}_3$. While nitrogen is supplied from ambient air, it is the production of the hydrogen that costs energy. Most commonly hydrogen is produced from natural gas, coal or heavy oils.

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. The thermodynamic minimum energy requirement is 20 GJ/ton NH_3 [1]. 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% [4]. 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) [8].

Once ammonia is produced, it can be used to make straight nitrogen fertilisers (a straight fertiliser is defined as to contain only one primary nutrient) – or together with phosphate, potassium or micronutrients to make compound fertilisers (a compound fertiliser is defines as to contain two or more primary nutrients) [9]. 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 nitric acid is then reacted with the remaining ammonia to produce ammonium nitrate.

The GHG emissions associated with nitrogen fertiliser production is CO_2 from the carbon in the fossil fuels used. Further, in the production of nitric acid, nitrous oxide (N_2O) 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.

The hydrogen needed for ammonia production in the Haber-Bosch synthesis can also be produced from renewable resources. This opens up for a more sustainable production of food, feed, fibres and fuels. There are four main options available for the production of renewable hydrogen [10, 11]: (1) electrolysis based on renewable electricity; (2) reforming of biogas; (3) thermal conversion of biomass (e.g. pyrolysis and gasification) and (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. While technology for hydrogen production via electrolysis is well established, the biomass gasification is still on a demo level [12]. Production of hydrogen by reforming of biogas (2) and thermal gasification (3) and thereafter synthesis to nitrogen fertilisers has been studied by [13, 14]. Collection of hydrogen produced by algae etc. (4) is so far only at laboratory-scale.

There have been some production facilities utilising electrolysis to produce 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 [15]. 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 techno-economic studies were carried out on electrolysis-based ammonia production, see for example Dubey [16], Jourdan and Roguenant, [17] and Grundt and Christiansen [18].

At present, the ammonia production based on renewables is becoming interesting again, as a measure to reduce fossil fuel dependency and to reduce GHG emissions. In Minnesota, USA, a plant is currently being commissioned that will produce 1 ton per day ammonia in a Haber-Bosch synthesis reactor, the hydrogen needed for the synthesis is derived from wind-powered electrolysis [19].

The aim of this study was to investigate the land use, energy use and GHG emissions from the production of ammonium nitrate based on biomass. Two technologies are studied, in three different scenarios. In one scenario ammonium nitrate production is integrated in an existing forest residues fired combined heat and power (CHP) where the electricity is used to drive an electrolyser, producing the required hydrogen for the ammonia synthesis. In another two scenarios, dedicated plants for nitrogen production was investigated assuming thermochemical gasification of biomass for hydrogen production, using either straw or short rotation coppice (*Salix*, i.e. willow) as raw material. Ammonium nitrate was chosen since it is the most commonly used nitrogen fertiliser in Sweden.

2. Method

The method used to evaluate the systems in the study was life cycle assessment (LCA). LCA is a methodology used for studying the potential impact on the environment caused by a chosen product, service or system. 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. The energy and material flows across the boundaries are looked upon as inputs (resources) and outputs (emissions) [20]. A distinction can be made between two types of LCA. Attributional LCA study accounts the

flows to and from a studied system but do not consider effects outside the system boundary. Consequential LCA, which is applied in this study, describes how flows will change in response to a possible decision and includes effects both inside and outside the life cycle of the studied system.

The consequential LCA take into account changes of a system by studying market reactions. A very important step in a consequential LCA study is to identify which marginal market changes takes place. This can often be decisive for the outcome of the study. However, identifying the marginal production can be a rather complicated task.

First of all, it is important to distinguish between short-term and long-term marginal changes. Short-term marginal production is the last unit to be taken into production when demand increases and will be the unit with the highest operation costs. The long-term marginal production involves changes in capacity, i.e. instalment of new plants as a response to a change in demand [21]. Further, the geographical location is also important for the choice of marginal data. For example, in certain locations there are physical limitations to market exchange, e.g. when heat production or consumption is involved, or when bottlenecks exist in the electricity transmission system [22]. Additionally, regulatory systems can distort the market and have an influence on the marginal production. As Finnveden [23] points out, introducing CO₂ caps in the EU electricity market could lead to a renewable fuel being on the margin, or more likely a complex mix of different types of energy sources.

A number of methods and energy prediction models are available to establish the marginal energy production, but it tends to be very difficult to reflect the effects in a proper way and the results are therefore highly uncertain [22]. It can also be done in a more simplistic way by assuming a single marginal technology. In a review of consequential LCA studies, Mathiesen et al. [22] found that most studies identified coal CHP as the marginal production for electricity, whereas the results for heat were more varied. In the majority of the studies reviewed, a long-term time horizon of 10–20 years was used. The choice of marginal production for this study is further treated in chapter 3.

The energy balance is calculated as primary energy (Table 1). The characterisation factors for global warming were chosen for a 100-year perspective; fossil CO₂: 1, CH₄: 25 and N₂O: 298 (IPCC, 2007). CO₂ from biomass was assumed to not contribute to global warming, with the argument that the CO₂ released at combustion has recently been captured by the biomass in question. While this at present is standard procedure in LCA, there is also an emerging discussion that the time lag between capture and release of CO₂ inherent to perennial bioenergy must be considered (see e.g. [24]). The methodology is however far from settled and was not included in the present study.

Table 1. Primary energy factors used in the study [25]

Energy source	Factor	Comment
Diesel	1.06	Factor for production and distribution
Natural gas	1.06	Factor for production and distribution
District heating (oil)	1.27	Factor for production, distribution and conversion losses
Electricity (coal)	2.72	Factor for production, distribution and conversion losses

The land use is expressed as the number of hectares needed per functional unit (FU). It is 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. 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 (DLUC). In recent years, however, there have been discussions to also include indirect land use change (ILUC) in LCA. 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 [26]. However, ILUC can not be observed, quantification requires the use of e.g. economic equilibrium models and the results are associated with high uncertainty. While DLUC is included in the base case of this study, ILUC is further treated in the sensitivity analysis.

The functional unit in this study was set to the production of 1 metric ton 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. System description

In scenario 1, nitrogen fertiliser production integrated into an existing CHP plant is studied. At present, forest residues is the main biomass used in Swedish CHPs [27]. 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 1). In scenario 2 (straw) and 3 (Salix), a new plant utilising thermal gasification technology to produce hydrogen for fertiliser production is studied. Straw and Salix has been pointed out as promising future possible biomass energy sources, especially in combination with gasification technology [28]. The “green fertilisers” produced were assumed to replace the use of other types of marginal nitrogen.

As previously mentioned, the choice of replaced marginal production is vital for consequential LCA studies and closely connected to the choice of geographical scope. In the case at hand, we study use of Swedish raw material for production of nitrogen fertilisers in Sweden. The geographical scope is therefore set to Sweden. Next step is then to identify the marginal production in Sweden, of heat, electricity and nitrogen fertilisers. In this study we apply a simplified reasoning of the marginal production, to identify the short-term marginal.

The electricity market in Sweden is integrated together with the other Nordic countries (Denmark, Finland and Norway). Besides the Nordic countries, Sweden is able to import and export electricity from Germany and Poland; two countries that are highly dependent on coal fired power generation (in Poland 89 % of all electricity was coal condensation power in 2008; in Germany 46 %). Import from these countries only happens when all other alternatives have been exhausted and as backup power [29]. We therefore assumed coal power as the marginal technology for electricity.

The local district heating networks are well developed and are available in more than 270 out of Sweden's 290 municipalities. The fuel mix has transitioned from primarily fossil to nowadays being

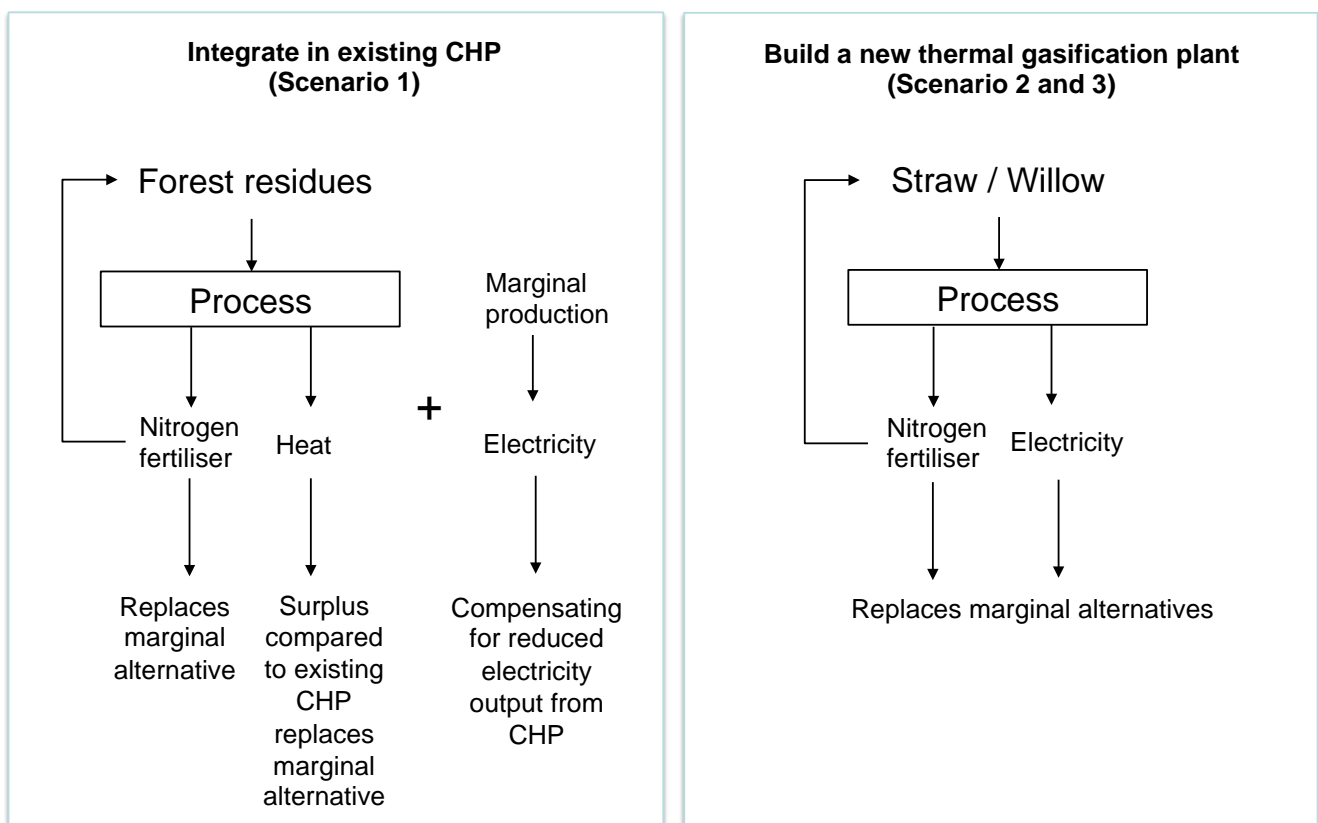
mainly bio-based. The peak heating load is however often natural gas or oil [29]. Based on this, we assumed that fossil oil is the marginal production for district heating.

There is no production of nitrogen fertilisers in Sweden, but all is imported. However we found no studies or statistics on the origin of the imports. The European nitrogen industry is about to be included in the EU emission trading system, making it costly for them to emit greenhouse gases. Therefore the marginal production was assumed to be an older natural gas plant without nitrous oxide removal, with emissions of 7.3 kg CO₂-eq/kg N, based on data in [4].

To highlight the uncertainty in assumptions of marginal production, Finnveden [23] recommends that two scenarios be used in LCAs, one high CO₂ emission marginal alternative and one with low CO₂ emissions. In this study a low CO₂ emissions scenario is applied in the sensitivity analysis.

In all scenarios, a net production of 165 ton N per year of ammonium nitrate was modelled. Most new nitrogen fertilisers built today based on natural gas are much larger; 1000-1500 ton ammonia per day is common, with up to 5000 ton per day [30, 31]. The large scale of the ammonia facilities is not so much because of technical constraints but due to economies of scale. The technical details in the scenarios are further described in [32].

Figure 1. Visual description of the studied scenarios.



3.1 System boundaries and delimitations

The raw material was assumed to be of Swedish origin. 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 produced fertiliser was therefore not included. However, fertilisers are needed in cultivation. Therefore it was assumed that part of the ammonium nitrate produced is returned to the plantation/field (Figure 1). For willow (*Salix*) plantations, the amount of returned nitrogen was according to the fertiliser recommendations [33], while for straw and forest residues the amount of returned nitrogen was calculated as the amount of nitrogen removed with the straw/residue [34]. 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 [35].

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) [36, 37].

3.2 Cultivation/collection of biomass raw material

The yield of straw was calculated to 4.3 ton dry matter per hectare and year, based on the 5-year average of winter wheat yield (2005-2010) [38] and multiplied by a straw harvest factor of 0.85 [39]. Data on the energy use for windrowing, baling and collection were taken from Nilsson [40]. 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 [41]. For forest residues, it was assumed that 32 wet ton of residues per hectare are collected after final felling [42]. 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 [43].

3.3 Land use and soil carbon

In scenario 1, forest residues are used as the raw material for nitrogen fertiliser production. Harvesting forest residues leads to no actual land use as it is a by-product from forestry. This is under the assumption that the residues previously are not utilised for any other purpose and therefore has no indirect effects on land use. However, forest residues contain some carbon that would have been left in the forest if not utilised. In a study by Lindholm [43], 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 [43]). 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.

In scenarios 2, straw was assumed to be used as raw material. Similar to the forest residues, 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. 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) [44]. Here we assume that there is enough straw available for harvesting that is currently not utilised.

However, harvesting straw can have an impact on the soil carbon content. Straw incorporated into soil will decompose, but part will be transferred to the long-term soil carbon pool. The rate of decomposition and transfer to long-term carbon pool 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) [45].

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 [46]. 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 [45], 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). In a long-term field trial in Sweden [47], removal of straw showed 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 [48].

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 [7].

In scenarios 3, willow (*Salix*) was assumed to be used as raw material. At present, only 13 000 ha of *Salix* are planted in Sweden [49]. However, the potential is reported to be as large as 200 000 ha [28]. In 2010, about 6.7% (equal to 176 800 ha) of Swedish farm land is under fallow [49]. There is also a great deal of abandoned farmland; the cultivated area has declined by about 300 000 hectares since the 1970s [28]. 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 [50]. It is reasonable to believe that increased planting of *Salix* will take place on all these different types of land. It is difficult to foresee how land use will develop on Sweden, but we assume that at least the reported potential of 200 000 hectares of land can be utilised for *Salix* plantation without any indirect land use changes. *Salix* is a perennial crop with a large root system. Planting *Salix* will therefore often have a positive effect on soil carbon content. A combination of different previous land uses was assumed here (Table 2).

Table 2. Soil carbon change when Salix is planted on different types of land and the assumed share of each land type converted

Type of land	Soil carbon change (kg C/ha year)	Assumed share of land used to plant Salix
Fallow farm land (mineral soil)	+500 ¹	50%
Fallow farm land (organic soil)	+1700 ²	5%
Previously ley	0 ¹	25%
Abandoned farm land	0 ³	20%

¹Ref: Börjesson (1999)

²Ref: Berglund and Berglund (2010)

³The quality of abandoned farm land varies, which makes it difficult to assess the effect of cultivating Salix. We assumed that on average, there is no change 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 CO₂-eq/ha and year) based on data in Table 2. 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.

3.4 Transport of biomass raw material

The transport distance for biomass was calculated using the model described in [51] and [52]. 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. The transport distance was estimated to be 100, 70 and 44 km respectively in scenario 1, 2 and 3.

3.5 Nitrogen fertiliser production

In scenario 1, solid oxide high temperature electrolysis was assumed for the hydrogen production, utilising electricity (120 MJ/kg H₂) and steam (28 MJ/kg H₂), data collected from Zeng and Zhang [53]. For the thermochemical conversion route, the hydrogen yield and electricity requirement were based on data found in Hamelinck and Faaij [54] and emissions data from Edwards et al. [55].

The hydrogen is together with nitrogen gas synthesised to ammonia. The nitrogen gas was assumed to be produced in a cryogenic air separation plant. 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. Energy consumption and steam production for the ammonia synthesis were assumed to be similar to those of a natural gas-based system [56, 57].

Nitric acid is produced by the exothermic reaction of ammonia and air over a catalyst and the absorption of the product gas in water. Half of the produced ammonia was assumed to be converted to nitric acid. Data for yields, electricity use and steam production were taken from [58] and [59]. In the reaction, N_2O is 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 [58]. Here we assumed 0.6 kg/ton nitric acid (100%), which recalculated can be expressed as 2.8 g N_2O /kg N.

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 [60]. The ammonium nitrate is thereafter granulated. The electricity requirement is relatively small, 90 MJ/ton ammonium nitrate produced [61].

4. Results and Discussion

4.1 Energy balance

The calculated primary energy input and avoided primary energy use due to export of surplus heat and electricity are presented in Table 3. The results are presented as per ton N net output, i.e. after deduction of the use of some of the nitrogen in the biomass plantations.

There is no input of external energy to the production plants, the biomass serves both as raw material and energy source to drive the processes. In scenario 2 and 3, more energy is avoided than is put in. However in scenario 1, more energy is put in than avoided, mainly due to the assumption that the missing electricity is produced with coal power with low energy efficiency. Biomass input represents a large post. It can however also be interesting to study the fossil energy balance. In this case, the energy balance in that case gets even more favourable for scenario 1 and 2, with very low inputs and large avoided energy use. For scenario 1, there will however still be a net energy use.

4.2 Land use

The land use for Salix was calculated to be 0.22 ha per ton N produced. This is the direct land use without any deductions for by-products.

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 0.5 ha cereal cultivation. For forest residues, the production of 1 ton N requires collection of residues from around 25 ha of felled forest.

Table 3. Energy inputs and surplus energy to produce 1 ton N in the form of ammonium nitrate (after a certain amount of nitrogen has been returned to the biomass plantation).

	1 (Forest residues – integration in existing CHP)	2 (Straw – new thermal gasificati on plant)	3 (Salix – new thermal gasifica tion plant)	Unit
Biomass input	106	40	41	GJ/ton N net
Energy for cultivation, harvest and transport	2	1	1	GJ/ton N net
Energy to replace missing electricity	78	--	--	GJ/ton N net
Avoided energy due to electricity surplus	--	3	3	GJ/ton N net
Avoided energy due to heat surplus	14	--	--	GJ/ton N net
Avoided energy due to replacement of fossil fertilisers	53	53	53	GJ/ton N net
Sum (Inputs – Avoided)	119	-14	-14	GJ/ton N net

4.3 Greenhouse gas emissions

The GHG emissions per functional unit for the different scenarios are presented in Table 4. All the scenarios show a net reduction in GHG.

As explained in the previous section, the primary energy use is larger than the avoided energy use 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 (2 and 3) 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.

Table 4. Emissions of greenhouse gases expressed as ton CO₂-eq/ton N, after deduction of internal requirements for biomass production

	1 (Forest residues – integration in existing CHP)	2 (Straw – new thermal gasification plant)	3 (Salix – new thermal gasification plant)
Biomass production and transport	0.2	0.1	0.2
Soil carbon emissions/uptake	0.3	0.3	-0.3
Nitric acid production	0.4	0.4	0.4
Excess heat	-1.0	0.0	0.0
Excess electricity	--	-0.2	-0.2
Reduced electricity production	4.8	--	--
Subtotal	4.7	0.6	0.2
Replacement of fossil nitrogen	-7.3	-7.3	-7.3
Total	-2.6	-6.7	-7.1

4.4 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 sensitivity analysis for a number of selected parameters that have a large influence on the results.

Changing the functional unit to 1 hectare was tested for the scenarios studied, the results are presented in Table 5. For the functional unit 1 hectare, Salix thermal gasification scenario gave the largest reduction in GHG, since more nitrogen per hectare is produced than in the other scenarios. Contradictory, per functional unit ton N, the results show no large difference between straw and Salix. For forest residues, there is almost no reduction at all in GHG emissions when expressed as per hectare; this is since the residues is divided over the forest rotation period giving a very low average annual yield. The decision on what is the most relevant functional unit can be discussed. Cherubini [62] e.g. recommends that LCA of bioenergy crops be expressed on a per hectare basis. 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. In this study however the aim was to study the production of nitrogen, and we found that 1 kg nitrogen was the most relevant functional unit. The functional unit 1 hectare however gives further insight of the systems, which can be important for decision making.

When producing excess heat or electricity, in the base case it was assumed that fossil energy will be outcompeted on the energy 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. [25]). This has a certain influence on the results (Table 6); however there is still a net reduction in GHG emissions in scenario 2 and 3. For scenario 1, the missing electricity was in the base case assumed to

be compensated for by fossil based electricity. If it is replaced by renewable electricity, the GHG savings will be much larger.

Table 5. Emissions of greenhouse gases expressed as ton CO₂-eq/ha and year, after deduction of internal requirements for biomass production

	1 (Forest residues – integration in existing CHP)	2 (Straw – new thermal gasification plant)	3 (Salix – new thermal gasification plant)
Biomass production and transport	0.01	0.11	0.91
Soil carbon emissions/uptake	0.01	0.55	-1.23
Nitric acid production	0.02	0.76	1.86
Excess heat	-0.04	0.00	0.00
Excess electricity	0.00	-0.29	-0.72
Reduced electricity production	0.19	0.00	0.00
Subtotal	0.19	1.13	0.82
Replacement of fossil nitrogen	-0.29	-13.6	-33.4
Total	-0.10	-12.5	-32.4

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 CO₂-eq/kg N. However, the emissions can vary depending on raw material, type of technology and age of the production plant (Table 6). In the sensitivity analysis, we tested the results of bio-based nitrogen replacing both a high emitting coal-based ammonia (9.7 kg CO₂-eq/kg N) and low emitting natural gas-based ammonia produced in a modern plant (2.8 kg CO₂-eq/kg N). The result is that in scenario 1, there will be no GHG saving, if the bio-nitrogen replaced low emitting fossil-based nitrogen.

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. 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 to having no significant impact at all (see section 2.3). 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). Removing forest residues was tested for losses of between 3 and 50 kg C/ha and year. The results of the soil carbon sensitivity analysis are presented in Table 6. As can be seen, soil carbon has an influence on the global warming results, especially in the Salix CHP scenario.

Table 6. Reduction of GHG emissions (i.e. a large number is beneficial), for the base case and for a number of different sensitivity analysis scenarios. For each sensitivity analysis scenario, a minimum and maximum value for the changed parameter is used.

Scenario number	Heat and electricity		Replaced nitrogen		Direct land use change		Indirect land use change	
	Fossil (=base case results)	Renewable	Low	High	Low	High	Low	High
1 (Forest residues - integration in existing CHP)	2.6	5.9	-1.9	5.0	1.6	2.8	--	--
2 (Straw – new thermal gasification plant)	6.7	6.5	2.2	9.1	6.2	7.0	--	--
3 (Salix – new thermal gasification plant)	7.1	7.0	2.6	9.5	5.8	8.2	3.3	6.7

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, 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 and/or intensification of production. The models are very complex and the results are associated with high uncertainty. In a review study the figure was found to vary between -50 and 100 g CO₂-eq per MJ biofuel, with extremes up to 300 g CO₂-eq per MJ [63].

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 (high estimate), according to the variation reported by Edwards et al. [64]. 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 scenario are presented In Table 6. 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.

4.5 Cost of production

However important GHG reduction, the price competitiveness of green nitrogen will be decisive for commercial introduction. The average 2011 world market price for urea was 421 US dollars per ton [65], equivalent to around 6 SEK per kg N. The ammonia price is related to the natural gas price, and subsequently also to the oil price [66]. Abram and Forster [67] report that natural gas feedstock makes up 90% of ammonia production costs. In this study, we did not make a cost calculation. However, in a study by Ahlgren et al. [68], the cost of producing ammonium nitrate based on electrolysis for hydrogen production in a large-scale biomass CHP was estimated to cost 8 SEK per kg N, slightly over the world market price for fossil-based fertilisers. Biomass feedstock represented a large cost, but also investment in plant equipment. However, as there is no biomass based nitrogen production at present the modelling was built on many assumptions, and the results are therefore connected to large uncertainties.

4.6 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 [49]. In this study, 165 ton per day net nitrogen was assumed to be produced in each scenario. To supply Sweden with nitrogen, three such plants would be required.

In the straw scenario, around 7.2 PJ 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 11-14 PJ per year [69].

For the Salix scenario, around 36 600 ha of plantations would be needed to supply Sweden with green nitrogen. This can be compared against the total Salix area in Sweden at present, which is 13 000 ha (equivalent to ca 0.5% of Swedens farmland).

Around 18 PJ per year of forest residues would be required to supply Sweden with nitrogen. The available statistics on forest residue harvesting are uncertain, but it is estimated that forest residues were harvested on 85 000 ha (41% of total final felling area) in 2008 [70]. The amount of forest residues per hectare varies between regions and types of stand, but using an average of 217 kg dry matter per hectare and year (see section 3.2) the harvested amount of forest residues in 2008 was equivalent to 28 PJ. Forest residues is today mainly utilised in industry and district heating for heat and power production [71]. Hence, there seems to be sufficient forest residues, and the potential to increase harvesting is large.

4.7 Using green fertilisers in crop production

The emissions from rapeseed cultivation when using fossil based nitrogen (7.3 kg CO₂-eq/kg N) or the green nitrogen studied in this paper, are presented in Table 7. Data was collected from Bernesson [72] for everything except production of nitrogen fertilisers. The yield was assumed to be 2 470 kg/ha (8% moisture content) and the amount of nitrogen fertiliser used 140 kg N/ha. It is evident that the use of green nitrogen can significantly lower the GHG emissions from cultivation of rapeseed.

Table 7. Greenhouse gas emissions from cultivation of rapeseed when using different types of nitrogen fertilisers, g CO₂-eq/kg rapeseed.

	Type of N used			
	Scenario	3	2	3
	Fossil		(Straw – new thermal gasification plant)	(Salix – new thermal gasification plant)
Seed	3	3	3	3
Production of P&K fertilisers	24	24	24	24
Production of N fertilisers	413	266	34	3
Soil emissions	329	329	329	329
Production of pesticides	2	2	2	2
Tractive power	72	72	72	72
Heat for seed drying	30	30	30	30
Machinery inputs	2	2	2	2
Total emissions	875	728	496	465
Savings, % of fossil case	0%	17%	43%	46%

5. Conclusions

The production of mineral nitrogen is one of the largest fossil energy inputs in Swedish agriculture. However, we have shown that mineral nitrogen can be produced based on renewable energy. This would lower the dependence on fossil energy in food production. The results showed that GHG emissions and use of fossil energy can be significantly lowered compared with fossil-based fertilisers, even when indirect land use changes are considered.

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.

It is however very difficult to draw general conclusions regarding choice of technology and raw material for production of green nitrogen, as results are highly dependent on the local context. Further, only energy balance and GHG emissions were assessed in the present study. 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 bioenergy system, such as eutrophication, acidification and impacts on biodiversity.

Food safety could be another impact that needs to be evaluated. Nitrogen is a vital component in maintaining high yields in crop production. We will sooner or later run out of fossil fuel. Without nitrogen fertilisers it will be difficult to feed and fuel a growing world population. We argue that of all the fossil energy we use, one of the first things we should replace is energy for nitrogen production. In that way we can secure future food, feed and bioenergy 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.

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