Ricardo
Energy & Environment

# Ammonia on-farm

## Life cycle assessment of different ammonia uses on a farm

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# Executive summary

Using life cycle assessment, this study compared three uses of ammonia produced via a Haber-Bosch facility on a remote farm in Scotland. The three ammonia uses compared in this study are:

- Aqueous ammonia fertiliser
- Ammonia vehicle fuel
- Ammonia CHP

These uses were compared with traditional alternatives:

- Urea fertiliser
- Diesel tractor
- Natural gas CHP

## System and outputs

The Haber-Bosch system is powered by a 500-900 kW wind turbine, which over the course of a year is assumed to deliver 1,470 MWh of renewable energy for ammonia production. The study's system uses this energy to produce 143 t of ammonia. Sending all of this ammonia to any one system delivers:

- 3,147 Ha fertilised land
- 2,884 ktkm of tractor trailer transport
- 335 MWh of combined heat and power.

## Findings

The study found that aqueous ammonia fertiliser provided the largest environmental benefit out of the three ammonia uses. While ammonia vehicle fuel and ammonia CHP were found to provide environmental benefits across most indicators, in some areas the traditional alternative was preferred. This was not the case for ammonia fertiliser.

Normalising the system's impacts in terms of European People Equivalents[1], suggests that marine ecotoxicity is the key indicator, since impacts on this indicator amounted to many more EPEs than the other indicators.

Sensitivity analysis into soil type and alternative fertilisers served to reinforce aqueous ammonia's environmental credentials.

The study's farm was found to have production capacity that exceeded its fertiliser need. An assessment examining whether to export excess aqueous ammonia or use ammonia for CHP and vehicle fuel revealed that both systems delivered a net environmental benefit across all indicators. However, it is this study's conclusion that the export scenario is preferred since it delivers a marine ecotoxicity benefit equivalent to -1,000EPEs compared to -438EPEs in the no export scenario. A transport burden greater than the length of Scotland is required for the no export scenario to deliver a larger marine ecotoxicity benefit.

[1] EPE: the impact inferred for one European, deduced by dividing the total estimated impact from Europe by its population.

# Glossary of acronyms

Acknowledging that this study uses a lot of acronyms, the table below compiles all their definitions for ease of reference.

**Table 1: Table of Acronyms**

| Acronym | Explanation |
|---|---|
| ASU | Air Separation Unit |
| BEIS | UK Government Department for Business, Energy and Industrial Strategy |
| CHP | Combined Heat and Power |
| CML | Centrum voor Milieuwetenschappen Leiden (Centre for Environmental Studies, University of Leiden, Holland) |
| $CO_2$ | Carbon Dioxide |
| 1,4-DCB | 1,4-DiChloroBenzene |
| EPE | European Person Equivalents |
| EU | European Union |
| GWP | Global Warming Potential |
| $H_2$ | Hydrogen |
| Ha | Hectare |
| ISO | International Standards Organisation |
| ktkm | kilotonne-kilometre (unit of freight) |
| kW | kilo-Watt |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| MJ | Mega-Joule |
| MW | Mega-Watt |
| MWh | Mega-Watt-hour |
| N, $N_2$ | Nitrogen |
| $NH_3$ | Ammonia |
| NOx | Oxides of Nitrogen |
| QA | Quality Assurance |
| SRUC | Scotland's Rural College |
| STFC | Science and Technology Facilities Council |
| UAN | Urea Ammonium Nitrate |

# Table of contents

**Appendices**

# 1 Introduction

The Science and Technology Facilities Council[2] (STFC) commissioned Ricardo Energy & Environment[3] (Ricardo) to deliver a life cycle assessment (LCA) of the environmental impacts associated with three uses of ammonia produced on a remote farm via renewable energy:

- Ammonia fertiliser
- Ammonia vehicle fuel
- Ammonia for CHP

The impacts of these three systems are compared against traditional alternatives. This report sets out the findings of the study.

## 1.1 Ammonia

Ammonia ($NH_3$) is a highly flexible fuel with strong logistical advantages, as huge quantities of ammonia are already created and distributed globally. When produced using renewable electricity, it is carbon-free, so ammonia is a candidate fuel for future green energy systems. There are well-established production methods, handling procedures and distribution channels for ammonia, as well as dedicated international markets. Ammonia can be used in fuel cells, internal combustion engines and gas turbines at a range of scales to produce power, heat and motive power. For these reasons, some have spoken of the 'ammonia economy' as a rival to the fledgling 'hydrogen economy.'

While possessing a number of advantages, ammonia-based energy technologies have some important weaknesses. They are generally less fuel-efficient than competitors in life-cycle terms; this is especially relevant regarding cyclical processes such as energy storage. As a hazardous substance, policy makers are likely to raise safety requirements over ammonia use in densely-populated areas, which may add costs to ensure that safety requirements are met. Ammonia can cause acidification and encourages particulate matter formation if emitted directly to air, either via spillage or through exhaust systems if incompletely combusted. Moreover, the National Emission Ceilings Directive[4] sets national emission reduction commitments for Member States and the EU for five important air pollutants, which includes ammonia. The UK is within 1% of hitting its emission ceiling[5].

### 1.1.1 Ammonia in an on-farm scenario

This study focusses on a remote farm that is capable of generating a large amount of renewable energy but has a grid connection with limited export capacity. The study assumes that the farm has recently upgraded a wind turbine installation and is now generating more electricity than can be exported. It investigates using excess energy to produce ammonia on the farm, which can then be used for several purposes. The ammonia could be used as a fertiliser, as fuel for farm vehicles or as energy storage to be used to provide CHP.

It is assumed that the farm is located in northern Scotland, as this area is less densely populated and possesses a more constrained transmission and distribution network. However, it should be possible to translate most of the analysis to alternative "remote farm" scenarios, including overseas.

[2] http://www.stfc.ac.uk/
[3] https://ee.ricardo.com/
[4] https://www.eea.europa.eu/themes/air/national-emission-ceilings/national-emission-ceilings-directive
[5] https://www.eea.europa.eu/data-and-maps/dashboards/air-pollutant-emissions-data-viewer

# 2 Goal

The goal of this study is to understand the environmental impact of a remote farm producing ammonia from renewable energy to be used as: fertiliser; vehicle fuel; or Combined Heat & Power (CHP), offsetting the use of traditional alternatives.

This study compares aqueous ammonia fertiliser against urea; an ammonia/diesel tractor against a traditional diesel tractor; and ammonia CHP against natural gas CHP.

# 3 LCA Specification

Table 2 Overview of LCA specificationsummarises the key parameters and characteristics of the LCA study.

**Table 2 Overview of LCA specification**

| Item | Description |
|---|---|
| Scope | Cradle-to-grave impacts, excluding decommissioning, for a 200 Ha farm with a 500-900 kW turbine with annual generation of 1,500 MWh ~98% available for ammonia production |
| Process system boundary | Impacts downstream of the generation of wind power are included, with the exception of decommissioning. Extant farm infrastructure is excluded from the assessment. |
| Temporal system boundary | No explicit temporal boundary. Impacts from global warming are limited to a 100-year period (via the use of $GWP_{100}$ factors). |
| Geographical system boundary | No explicit geographical boundary. UK grid emissions factors are assumed to apply where applicable. |
| Functional unit | 1 year's ammonia production |
| Impact criteria | CML-IA characterisation factors and Cumulative Energy Demand characterisation factors. |
| Comparator systems | Urea, diesel tractor, natural gas CHP |

### 3.1.1 Scope

This study takes a cradle-to-grave perspective, focussing on all phases of the life cycle system of the ammonia production system and its use as fertiliser, vehicle fuel and/or CHP. This includes the manufacture and operation of the production facilities, the operation of ammonia activities and the construction of additional equipment required to accept the ammonia products – for example a fuel tank for the ammonia/diesel tractor. This study does not account for the impacts associated with the decommissioning and disposal of the ammonia system. This is due to limited data availability.
The study's system is predicated on a 500-900 kW turbine providing ~1,500 MWh of wind generated electricity. It is assumed that 98% of this energy is available for ammonia production.

### 3.1.2 System boundary

The study does not include construction of the wind turbine. It is assumed that the turbine has been constructed for a purpose other than ammonia production and that it is excess generation capacity that is being used for the ammonia. The wind energy is considered to arise burden free, as its capital burden is attached to the wind turbine's core purpose. This study does not attempt to assess whether it is worth constructing a wind farm to produce ammonia; rather, it examines whether it is worth using ammonia products as an alternative to traditional comparators.

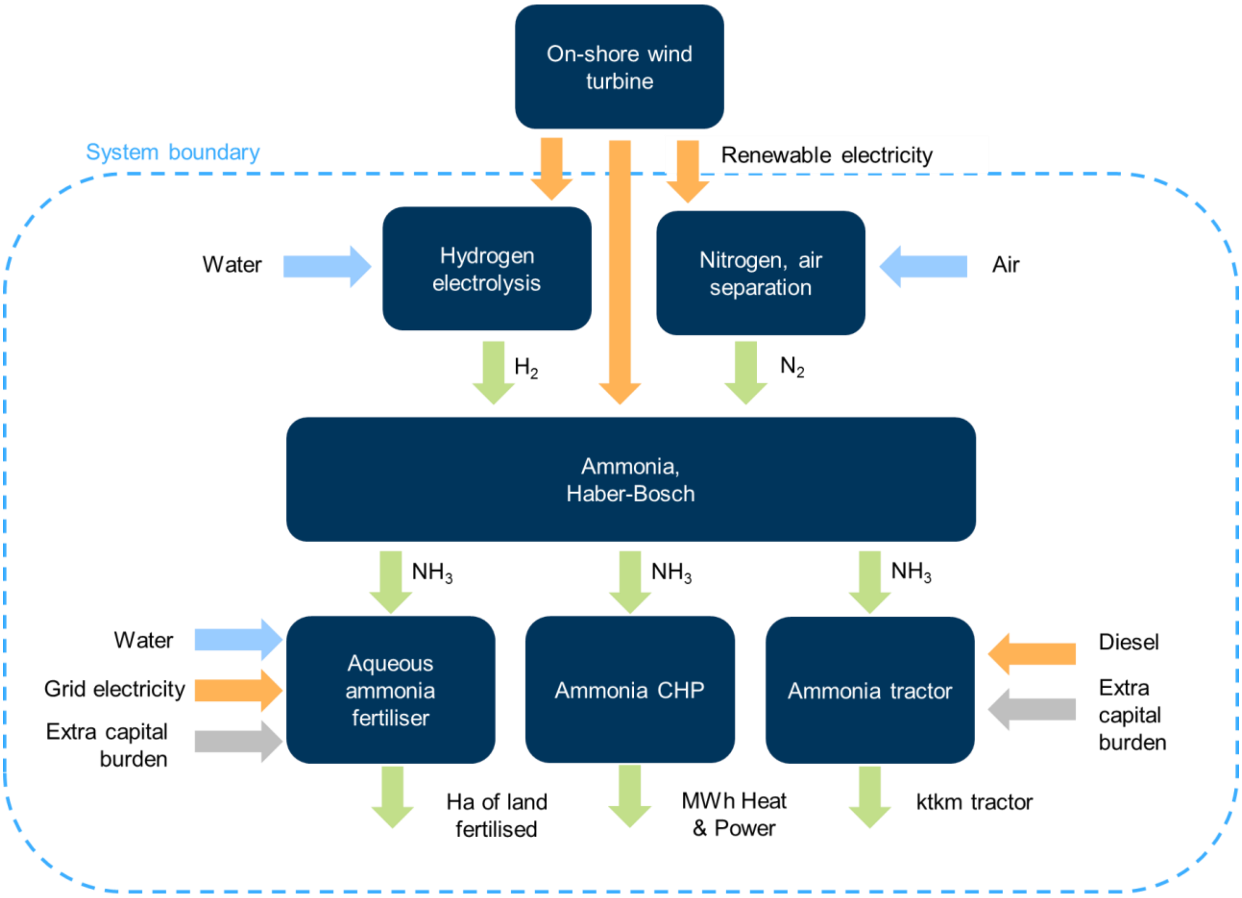
The study includes the construction of the hydrogen, nitrogen and ammonia plant. This includes the raw materials involved in these components. All impacts associated with the operation of these facilities are included in the study. However, as discussed above, their electricity consumption is assumed to arise burden free.

The construction of additional facilities for the production and use of the ammonia products, such as a mixing tank for the ammonia fertiliser and an additional fuel tank for the ammonia/diesel tractor, are included in the study. All material and energy inputs are included in the operation of the ammonia products. Any additional electricity requirements are assumed to be sourced via grid electricity rather than wind energy. UK grid emission factors have been used for these processes. This is illustrated in Figure 1 below.

As stated, the decommissioning and end-of-life stages are excluded from this study, mainly because of a lack of available data, though we also anticipate their burdens to be minimal. As such, the system boundary ends with the end of the useful operating life of the equipment.

There is no explicit temporal or geographical boundary placed on the impacts caused through the operation and construction of the system. The exceptions to this are that the impacts from greenhouse gas emissions are limited to a 100-year period (through the use of GWP100 values) and that all impacts from grid electricity are taken from the latest ecoinvent UK grid emission factor.

**Figure 1: System boundary schematic**




### 3.1.3 Functional unit

This study focusses on the environmental impact of using wind energy to produce ammonia to offset traditional farm activities. The functional unit is a year's worth of ammonia production. The study first calculates how much of each ammonia product can be produced with a year's supply of ammonia. This is expressed in units of Ha for fertiliser, ktkm for vehicle fuel, and MWh for CHP. The impact of producing an equivalent amount of the traditional alternative is then subtracted from the impacts associated with the ammonia product to determine the relative benefit/impact of the ammonia product. This relative impact enables the comparison of the ammonia systems on the basis of a year's production.

### 3.1.4 Environmental impact criteria

This study uses the CML-IA and Cumulative Energy Demand characterisation factors. These are described in more detail in the Methods Library for the SimaPro software[6]. The term 'method' refers to a system for handling impacts through a series of unified impact indicators. The characterisation factors used in this study are detailed below in Table 3.

**Table 3: Environmental Indicators**

| Impact | Unit | Description and rationale |
|---|---|---|
| Global warming potential (GWP) | kg $CO_2$ eq. | Contribution to global warming/ climate change; highly relevant to ammonia as a zero-carbon energy carrier. |
| Abiotic resource depletion | kg Sb eq. | Depletion of non-renewable mineral resources, excluding fossil fuels in this case; relevant if the 'ammonia economy' comes to fruition. Measured in kilogrammes of antimony extracted equivalent. |
| Primary energy consumption | MJ-eq. | Consumption of raw energy resources; highly relevant for an energy technology, represents net system energy efficiency. |
| Primary energy consumption (non-renewable) | MJ-eq. | Consumption of raw, non-renewable energy resources; relevant because ammonia can utilise, or give access to, renewable energy sources. |
| Acidification potential | kg $SO_2$ eq. | Acid formation potential; relevant as an effect caused by ammonia emissions to air and fossil fuel combustion, wide array of potential negative impacts. |
| Eutrophication potential | kg $PO_4$ eq. | Emissions of dangerous concentrations of nutrients to air, water or soil; relevant as ammonia is a source of nitrogen, a key cause of eutrophication. |
| Human toxicity | kg 1,4-DCB eq. | Emission of chemicals harmful to human health; a general evaluation of the health impacts of the systems on human health. |
| Terrestrial, freshwater and marine ecotoxicity | kg 1,4-DCB eq. | Emission of chemicals harmful to environmental health to land, freshwater and marine environments. Emissions to each of the three environments should be reported individually; a general evaluation of the health impacts of the systems on environmental health. |

[6] https://www.pre-sustainability.com/download/DatabaseManualMethods.pdf

| Impact | Unit | Description and rationale |
|---|---|---|
| Photochemical smog formation | kg $C_2H_4$ eq. | Emission to air of chemicals that encourage the formation of photochemical smog; relevant as ammonia could lead to a reduction in impacts of this type. |

## 3.2 System description

### 3.2.1 Ammonia synthesis

This study examines ammonia production via the Haber-Bosch process, which reacts nitrogen and hydrogen under high temperatures and pressures to form ammonia. The feedstocks to this process are hydrogen and nitrogen.

The system generates hydrogen via the electrolysis of water. It makes use of an alkaline electrolyser for these purposes. The Haber-Bosch process can work with unprocessed air, 78% of which is nitrogen. Despite this, the process is more efficient when using pure nitrogen. Additionally, the ability to store nitrogen prior to ammonia synthesis creates additional flexibility in terms of timing the use of feedstock electricity. An air separation unit (ASU) is used to isolate nitrogen from the air. The ASU modelled is a cryogenic air separation process, which involves the fractional distillation of air at low temperatures. This is the most cost-effective and efficient technology for generating nitrogen at scale (Bicer at al, 2016). As with the electrolyser, the system includes a small interim storage tank.

The Haber-Bosch reactor is based on a conventional design. As mentioned, this involves a high-temperature, high-pressure synthesis loop which reacts hydrogen and nitrogen to form ammonia. The reaction is exothermic, meaning that it can be self-sustaining once started. For these reasons, the process is not amenable to frequent stops and starts.

### 3.2.2 Ammonia fertiliser

Pure anhydrous ammonia can be used as fertiliser via soil injection and its use is common practice within the USA[7], where it represents 27% of fertiliser use. It is a nitrogen rich fertiliser with a nitrogen content of 82%[8]. However, Anhydrous ammonia requires specific soil conditions to avoid excessive loss to atmosphere. These soil conditions could not be expected in Scotland with any degree of certainty. Moreover, its use is uncommon in Europe.

Ricardo's expert judgement is to use aqueous ammonia as the most suitable ammonia fertiliser to produce in this system. Aqueous ammonia is simply anhydrous ammonia dissolved into water. It does not need to be stored under pressure, presenting a smaller risk to the operator, and tanks used for storing tractor fuel would be suitable for storing the mixture. However, aqueous ammonia has a lower nitrogen content than anhydrous ammonia (22% N) [9], and still requires soil injection, albeit to a lower depth than anhydrous ammonia. This will result in increased man-hours as a greater volume of fertiliser will be required to treat the same area.

### 3.2.3 Ammonia vehicle fuel

Ammonia was successfully being used as a vehicle fuel as early as the 1940s, where it was used as an alternative to fuels being consumed in the war effort[10]. It can be used within a fuel cell, within a

[7] Nitrogen demand and application type-global, International Fertiliser Association 2010
[8] http://www.soils.wisc.edu/extension/pubs/A2519.pdf
[9] http://www.soils.wisc.edu/extension/pubs/A2519.pdf
[10] Kroch E. Ammonia – a fuel for motor buses. J Ins Pet 1945;31:213–23

spark ignition engine or a compression ignition engine. Due to difficulties regarding ignition, it is advisable to use it as part of a dual fuel within an internal combustion engine.

While using ammonia within a fuel cell has significant advantages in terms of carbon emissions, the purpose of this study is to understand ammonia's usefulness on a remote farm. Outfitting a tractor engine within an ammonia fuel cell represents significant modification. Conversely, a diesel compression ignition engine requires little modification[11] to handle a dual diesel/ammonia fuel. It is for this reason, and the lower technology readiness level of ammonia fuel cells, that a dual diesel ammonia fuel has been selected for use in a compression ignition engine.

### 3.2.4 Ammonia Combined Heat & Power

Ammonia can be combusted for power generation in a similar way to natural gas or propane[12]. This study assumes that ammonia would be used in a 50 kW CHP unit where natural gas is substituted for an equivalent amount of ammonia based on energy content.

## 3.3 Comparators

### 3.3.1 Urea

Urea was selected as the comparator for the ammonia fertiliser. It is currently the most popular nitrogen fertiliser source with about 54% of the world market and represents the major sectoral growth in the nitrogen industry[13]. It is produced from ammonia and carbon dioxide, both of which can be produced through the steam reforming of natural gas. The two most commonly employed methods for the production of solid urea are prilling and granulation. Both lead to a solid fertiliser containing 46% nitrogen. Urea was applied to land via the same ecoinvent application process[14].

### 3.3.2 Diesel

A diesel tractor is chosen as the traditional comparator for the ammonia/diesel powered tractor. An ecoinvent process for transport via tractor, trailer was selected to model this process[15], albeit the capital burdens associated with existing farm equipment were removed from this process.

### 3.3.3 Natural gas

Natural gas was selected as the traditional comparator for the ammonia CHP system. Two ecoinvent processes, one for heat via CHP and one for electricity via CHP, are chosen to model this process[16].

## 3.4 Data Sources

It should be noted that this study is not based on a real system, operational or otherwise. As such, it has not been possible to obtain empirical information on certain processes nor details specific to a particular operational setup. Ammonia has not yet seen any substantial deployment. The purpose of this study is to provide a high-level assessment of possible uses for ammonia on a remote farm.

The intention is to understand if ammonia production might make environmental (or operational) sense when examined from first principles. As such, it is inevitable that there may be some

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[11] Life cycle assessment of ammonia utilization in city transportation and power generation pp1595
[12] Life cycle assessment of ammonia utilization in city transportation and power generation pp1599
[13] International Fertiliser Association https://www.fertilizer.org/En/Knowledge_Resources/About_Fertilizers/About_Fertilizers_Home_Page.aspx?WebsiteKey=411e9724-4bda-422f-abfc-8152ed74f306&hkey=b5314211-294c-4925-87a1-a1dc2c6cbe11&New_ContentCollectionOrganizerCommon=2#New_ContentCollectionOrganizerCommon
[14] https://v33.ecoquery.ecoinvent.org/Details/UPR/da0ee712-527d-410d-b3fa-73a69a115190/8b738ea0-f89e-4627-8679-433616064e82
[15] https://v33.ecoquery.ecoinvent.org/Details/UPR/aecab77c-e4e4-42f0-bcdb-2e42fdc0098b/8b738ea0-f89e-4627-8679-433616064e82
[16] https://v33.ecoquery.ecoinvent.org/Details/UPR/eb2ef600-17cd-467d-961f-8030f7fabde6/8b738ea0-f89e-4627-8679-433616064e82

divergences between the model and the configuration of a real system. In other instances, the study will use estimations or proxies in place of empirical data where this is unavailable. Emission factors for the processes used in this study were calculated from ecoinvent data, using the life cycle assessment software SimaPro.

# 4 The LCA Model

The second stage of an LCA, as defined by ISO, is to compile the life cycle inventory. Before discussing this, and the impact assessment stage that follows, it makes sense to discuss the LCA model in Microsoft Excel® that was developed to hold these datasets, perform the calculations and assist with the subsequent interpretation.

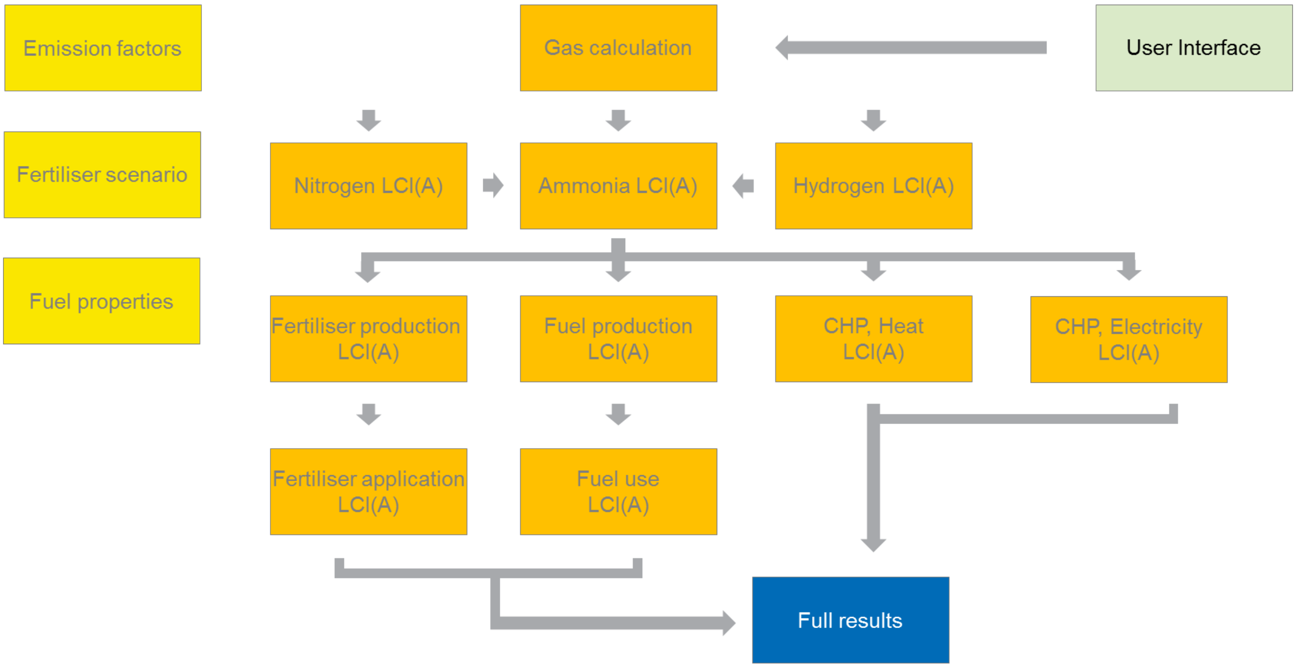
## 4.1 Model Design

Figure 2 below illustrates the LCA model design and how data flow through it. Sections in green represent user input, yellow sections land external data, orange sections perform calculations and the blue section presents the results.

The user interface specifies key variables such as how much energy is available for ammonia production, assumptions about the counterfactuals and the ratio of heat to power. The amount of available energy is allocated to hydrogen, nitrogen and ammonia within the gas calculation sheet, which ensures the right ratios are produced. The resulting years' worth of ammonia production (in tonnes) is passed to the fertiliser production, fuel production, CHP heat and CHP electricity LCI(A) sheets.

The emission factors sheet contains information from ecoinvent and SimaPro and enables the LCIA to be calculated on the relevant sheets. The fertiliser scenario contains options, which when selected from the user interface inform the fertiliser LCIA sheets. The Fuel properties sheet contains external information that informs the ammonia vehicle fuel and ammonia CHP systems.

**Figure 2: Model design schematic**



### 4.1.1 Intellectual Property

The intellectual property in the LCA model rests with Ricardo. Requests to access the model should be made to Ricardo via the contact details at the beginning of this report.

## 4.2 The Life Cycle Inventory

For this project, the life cycle inventory was compiled on a series of sheets. The datasets include:

- the capital burdens associated with the construction of facilities within the system boundary that cannot be assumed to already exist on the farm;
- material inputs and outputs, scaled to the unit operation's key output;
- all the energy inputs and outputs (identity and amount);
- all the by-products and wastes; and
- all relevant emissions to land, water and air.

### 4.2.1 Ammonia synthesis

As described above, this study assesses the production of ammonia via the Haber-Bosch process with Nitrogen supplied from an air separation unit and hydrogen supplied via electrolysis. Within the model, this is represented across three life cycle inventories: nitrogen production, hydrogen production and ammonia production. Each inventory details the capital burdens, material inputs and outputs, energy inputs and outputs for producing 1 kg of the relevant element. These inventories are scaled up to meet the amount of electricity available. The amount of electricity to pass to each of these inventories in calculated in a separate gas calculations sheet. This assumes that 6 kg of hydrogen and 28 kg of nitrogen are required for every 34 kg of ammonia. These ratios are then multiplied by the amount of electricity consumed per kg for each material to determine how much electricity to send to each inventory. The energy requirements are shown in Table 4 below.

A separate check is performed to ensure sufficient nitrogen and hydrogen is produced to feed the ammonia process. The final output of these inventories is a tonnage of ammonia.

**Table 4: Haber-Bosch energy requirements**

| Material | Ratio (kg) | Energy requirement |
|---|---|---|
| Hydrogen | 6 | 92% |
| Nitrogen | 28 | 5% |
| Ammonia | 34 | 4% |

### 4.2.2 Aqueous Ammonia production and application

The ammonia fertiliser system consists of two life cycle inventories within the model. The first concerns the production of the aqueous ammonia solution and includes capital burdens for mixing equipment, tap water and anhydrous ammonia, scaled to the production of 1 kg aqueous ammonia. Anhydrous ammonia makes up 25% of the solution. This inventory is scaled up to use all of the ammonia available from the ammonia production inventory to make as much aqueous ammonia as possible.

The second inventory concerns the application of fertiliser. An ecoinvent process for the application of plant product was modified to represent fertilising one hectare of land with aqueous ammonia. The inventory does not include capital burdens for the tractor and trailer, since these are assumed to be present on the farm already. Emissions from the tractor's use are taken from the original ecoinvent process and are scaled to 1ha of treated land. A volume of aqueous ammonia per hectare is determined by the Fertiliser Scenario sheet. This uses the User Interface's selected land management and crop choices to determine the nitrogen requirements per hectare and then calculates the volume of aqueous ammonia required to meet this nitrogen need. The aqueous ammonia application inventory is scaled to use all of the aqueous ammonia produced in the previous inventory to treat as many hectares as possible.

### 4.2.3 Ammonia-diesel tractor

The ammonia diesel tractor consists of two life cycle inventory sheets. The first produces the ammonia/diesel fuel blend in the correct ratio: sourcing 1 MJ's worth of ammonia and 1MJ's worth of diesel to produce a 50:50 fuel mix. This value is then scaled up to consume all the ammonia available and an equivalent amount of diesel. The resulting fuel blend is passed to the 'fuel use' inventory sheet. It is worth noting that the fuel production sheet is used simply to check the correct quantities of each fuel are sourced. An ammonia/diesel tractor would store ammonia in a separate fuel tank, blending the fuels as needed.

The fuel use sheet uses the amount of the ammonia/diesel fuel to transport via tractor as many tonne-kilometres of freight as possible. An ecoinvent process for tractor trailer freight was modified to include an on-board ammonia fuel tank and exclude the other capital burdens associated with producing the tractor (since it is assumed the tractor is already on the farm). Emissions are based on the original ecoinvent process, albeit emissions associated with the diesel content of the fuel are assumed to halve (since 50% of the energy content is now sourced by ammonia). It is expected that there will be higher $NO_x$ and $NH_3$ emissions from the ammonia content. It is assumed that the engine will have to meet regulatory requirements for these two emissions; consequently, the emissions profile has been set at the maximum limit for $NO_x$ and $NH_3$. This is 4g $NO_x$ per kWh mechanical output[17] and 0.01g $NH_3$ per kWh mechanical output[18]. The $NH_3$ limit is taken from the Euro VI limit; while this does not apply to off-road vehicles, it is reasonable to assume than an ammonia engine would have an ammonia emission cap and this standard provides a reasonable proxy. To calculate the emissions profile the engine's mechanical output is assumed to be 25% of the fuel energy.

### 4.2.4 Ammonia CHP

The ammonia CHP system is split between two processes, one producing Heat via CHP and one producing electricity via CHP. Both processes are based on the multioutput ecoinvent processes for heat, via natural gas cogeneration and electricity via natural gas cogeneration[19]. The Heat process is scaled to the production of 1 MJ, while the electricity process is scaled to the production of 1 kWh. Both systems are converted to MWh within the model. These processes were amended to substitute natural gas with ammonia on an equivalent energy basis. Natural gas has a higher energy content than ammonia (~49.5 MJ/kg compared with 18.8 MJ/kg), so this results in more ammonia being required than natural gas. The fuel requirements for natural gas and ammonia are shown in Table 5.

**Table 5: Fuel requirements for CHP**

| | Natural gas | Ammonia |
|---|---|---|
| Heat (1 MJ) | 0.035 kg | 0.093 kg |
| Electricity (1 kWh) | 0.18 kg | 0.47 kg |

Heat via CHP is more fuel efficient than electricity via CHP. To deliver 1MWh combined heat and power, 58% of fuel must be sent to the electricity process. The study's model includes functionality to alter the desired heat to power ratio. This is set at a default of 70% power and 30% heat. These values are combined with the system fuel efficiencies to apportion all of the available ammonia to the CHP processes.

[17] Euro Stage IV emission standards for nonroad diesel engines https://www.dieselnet.com/standards/eu/nonroad.php
[18] Euro Stage VI emission standards for heavy duty diesel and gas engines https://www.dieselnet.com/standards/eu/hd.php
[19] https://v33.ecoquery.ecoinvent.org/Details/UPR/eb2ef600-17cd-467d-961f-8030f7fabde6/8b738ea0-f89e-4627-8679-433616064e82

Emissions associated with the natural gas fuel have been removed from the process, while emissions for ammonia and nitrogen oxide are set at their regulatory limits. The limit for nitrogen oxide emissions is taken from Ecodesign regulation 813/2013 4 for cogeneration space heaters and is set at 120 mg/kWh fuel input. No suitable $NH_3$ limit was found for a cogeneration unit. As such the same ammonia ceiling of 0.01g/kWh used in the vehicle fuel process, was used as a proxy here.

### 4.2.5 Comparators

Ecoinvent processes were identified to model the comparator systems. These were modified to remove capital burdens associated with equipment already on the farm.

**Table 6: ecoinvent sources for comparator systems**

| | |
|---|---|
| Fertiliser production (Urea) | https://v33.ecoquery.ecoinvent.org/Details/UPR/3a7d8067-667a-43a4-b006-f28baa3a971a/8b738ea0-f89e-4627-8679-433616064e82 |
| Field sprayer | https://v33.ecoquery.ecoinvent.org/Details/UPR/da0ee712-527d-410d-b3fa-73a69a115190/8b738ea0-f89e-4627-8679-433616064e82 |
| Tractor, trailer | https://v33.ecoquery.ecoinvent.org/Details/UPR/aecab77c-e4e4-42f0-bcdb-2e42fdc0098b/8b738ea0-f89e-4627-8679-433616064e82 |
| CHP, Heat; CHP, Electricity[20] | https://v33.ecoquery.ecoinvent.org/Details/UPR/eb2ef600-17cd-467d-961f-8030f7fabde6/8b738ea0-f89e-4627-8679-433616064e82 |

## 4.3 The Life Cycle Impact Assessment

The LCI(A) sheets compile the life cycle inventories of the material and energy flows and then apply emission factors to determine the environmental impact of each individual flow. The emission factors are brought in from the Emission Factors sheet, which contains factors for every process and environmental indicator. The factors were calculated using the widely used modelling software SimaPro[21] by applying the CML-IA emission factors to various ecoinvent 3 datasets. ecoinvent is one of the world's largest and best-recognised repositories of life cycle impacts for products and processes. Values for primary energy consumption were calculated in the same way but used values from the Cumulative Energy Demand method to derive total primary energy consumption and primary energy consumption from non-renewables.

The Emission Factors sheet paired the incoming ecoinvent products and processes information (including the emission factor calculated by SimaPro), with the material flow names used within the model's LCI(A) sheets. This enabled the impact to be scaled by the amount of each material being modelled in the LCI(A) sheets.

## 4.4 Quality Assurance

Over the past couple of years, Ricardo has worked with the Modelling Integrity Team in the UK Department for Business, Energy and Industrial Strategy (BEIS) to apply its new QA standards to a range of our models. In 2016, we chose to adopt the BEIS assessment criteria for our own internal modelling QA procedures, so the methodology is now embedded in all our modelling work. On completion of the modelling, the model was audited against BEIS's assessment criteria (as adopted by Ricardo) and produced the QA Log that accompanies the report in Appendix 2.

[20] This is handled as two processes within SimaPro, one for low voltage electricity and one for heat. The UPR link is for the parent, ecoinvent multioutput process.
[21] http://www.simapro.co.uk/

# 5 Analysis of Results

## 5.1 Initial results

The following section details the initial results of the study. Before exploring the environmental impact, it is important to understand the system's output. Table 7 below shows how much ammonia could be produced on the farm over the course of year and how much each system could produce if it were allocated 100% of the available ammonia.

**Table 7: Model outputs**

| Material/Flow | Model Value | Model Units |
|---|---|---|
| Ammonia via Haber-Bosch | 143 | t |
| Fertiliser application to land | 3,147 | Ha |
| Transport, tractor and trailer | 2,884 | ktkm |
| Combined Heat & Power (CHP) | 335 | MWh |

Table 8 shows the net environmental benefit of each system, per tonne of ammonia. Please note this table reports on environmental benefit by taking the impact of the traditional comparator and subtracting the impact of the relevant ammonia system. Positive numbers in blue are preferred and indicate the ammonia system has a smaller impact than the traditional comparator. Negative results in red indicate the ammonia system has a larger impact than the traditional alternative.

**Table 8: Net environmental benefit per tonne of ammonia**

| Indicator | Unit | $NH_3$ Fertiliser | $NH_3$ Fuel | $NH_3$ CHP |
|---|---|---|---|---|
| Global warming potential | kg $CO_2$ eq. | **2,722** | **1,444** | **1,400** |
| Abiotic resource depletion | kg Sb eq. | **0.009** | -0.004 | -0.004 |
| Primary energy consumption | MJ-Eq | **54,019** | **20,601** | **22,361** |
| Primary energy consumption (non-renewable) | MJ-Eq | **52,968** | **20,731** | **22,431** |
| Acidification potential | kg $SO_2$ eq. | **14** | **13** | **1** |
| Eutrophication potential | kg $PO_4$ eq. | **3** | **3** | **0** |
| Human toxicity | kg 1,4-DCB eq. | **1,107** | **620** | -245 |
| Marine ecotoxicity | kg 1,4-DCB eq. | **1,390,523** | -348,699 | -281,840 |
| Fresh water ecotoxicity | kg 1,4-DCB eq. | **371** | -121 | -98 |
| Terrestrial ecotoxicity | kg 1,4-DCB eq. | **2** | -2 | -2 |
| Photochemical smog formation | kg $C_2H_4$ eq. | **0.56** | **0.14** | **0.20** |

Each system leads to a net reduction in global warming potential, primary energy consumption, acidification potential, eutrophication potential and photochemical smog formation. It is clear to see that the ammonia fertiliser system is preferred, leading to net benefits across each environmental indicator. This is due to the high burden associated with producing the traditional urea fertiliser that is used as a comparator. This is shown in more detail in Figure 3 to Figure 5.

The ammonia CHP system results in reduced primary energy consumption compared to ammonia fuel, but it has a lower global warming potential benefit and results in a net impact in human toxicity. Ammonia fuel and ammonia CHP systems both lead to large marine ecotoxicity impact.

Figure 3 to Figure 5 illustrate the environmental impact of the ammonia systems and comparators across a selection of environmental indicators. Charts for each environmental indicator are included in Appendix 1.

The bars should be reviewed in pairs (firstly the traditional comparator and secondly the ammonia system). It is important to note that comparison can only be made between bar pairings (comparator and ammonia system). For example, it is not meaningful to compare the impact of ~3,000 ktkm of tractor trailer transport with ~3,000 Ha of fertilised land. The impact of simply producing the ammonia is shown in isolation in the last bar (this impact is included within each of the ammonia system bars).

**Figure 3: Global Warming Potential (kg $CO_2$e) per year's ammonia production**

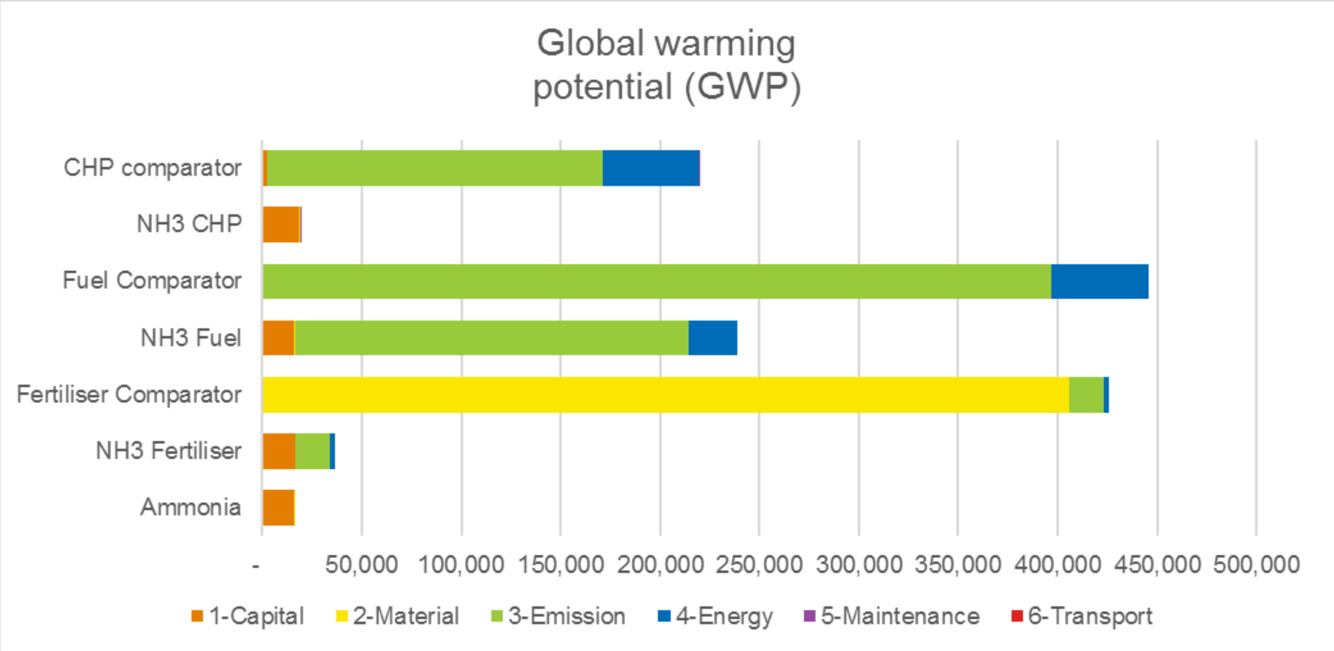



Figure 3 shows each ammonia system results in significantly smaller global warming potential than the counterfactual systems. For the ammonia CHP and fuel systems, this is due to the carbon free nature of ammonia resulting in a far smaller emission impacts. For the ammonia fuel system, we can see that the impact from emissions is roughly half the size of the diesel comparator. This is due to the ammonia fuel being blended with diesel on 50:50 basis. While the ammonia content results in higher volatile ammonia and $NO_x$ emissions, the pure diesel scenario results in far higher $CO_2$ and $CH_4$ emissions.

When comparing the fertiliser systems, it is the significant impact associated with producing the traditional urea fertiliser that is responsible for the difference between these two systems.

**Figure 4: Human toxicity (kg 1,4-DCBe) per year's ammonia production**

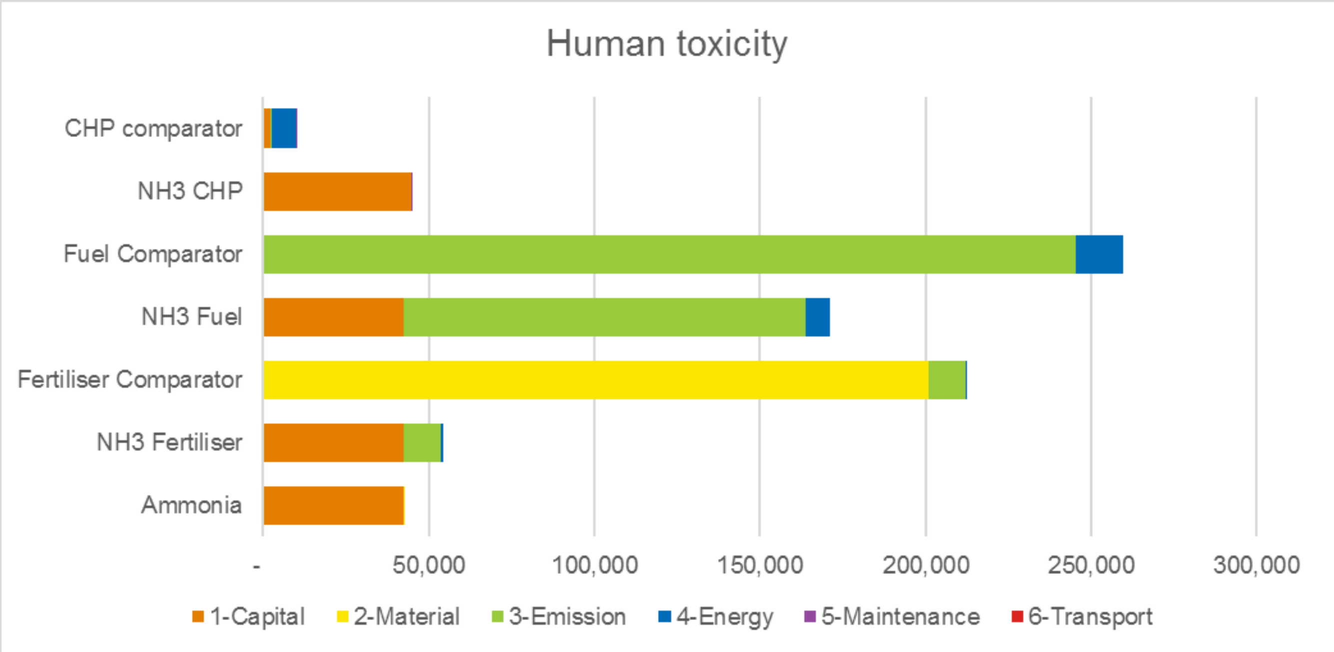



Figure 4 shows that, for the ammonia systems, the impact associated with the capital burdens of creating the ammonia facility is the largest contributor to the system's human toxicity impact, except for the ammonia fuel system. Whereas the ammonia fuel and ammonia fertiliser systems benefit from their comparators having an even larger human toxicity impact, the CHP comparator has a relatively small impact in this criterion. Within the fuel systems, benzene emissions associated with the fuel's diesel content are the largest contributor to human toxicity. Within the traditional urea fertiliser, chromium VI and Nickel emissions to air are the largest contributing factors.

**Figure 5 Marine ecotoxicity (kg 1,4-DCBe) per year's ammonia production**

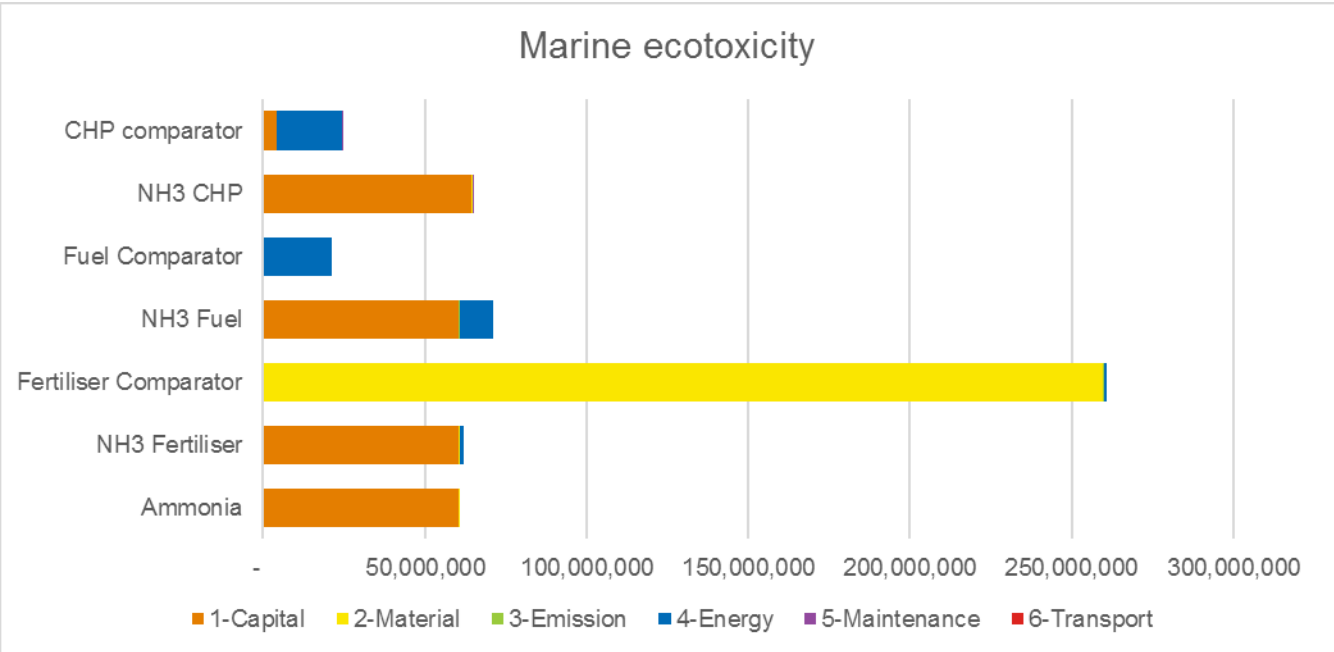


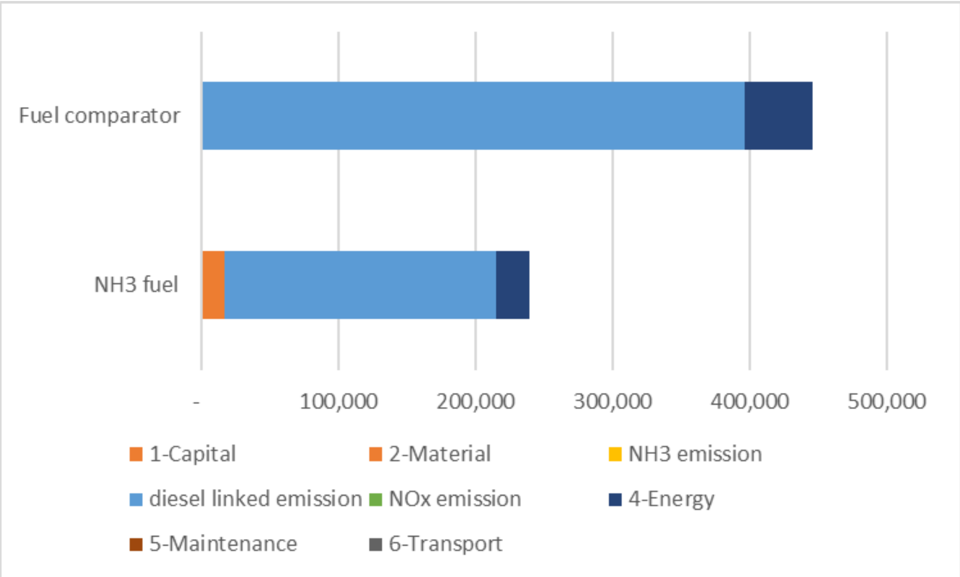

Figure 5 shows that the capital burdens associated with producing the ammonia results in a marine ecotoxicity impact that outweighs the impact of the traditional CHP and fuel systems. 84% of this capital burden impact is from the Haber-Bosch facility, with the hydrogen electrolyser making up the remainder. The impact associated with the nitrogen facility is less than 0.5%.

While the Ammonia CHP and fuel systems result in net impacts, the ammonia fertiliser system still delivers a net reduction in marine ecotoxicity due to the traditional urea fertiliser being burdened with a large marine ecotoxicity impact from beryllium emissions to water.

### 5.1.1 Comparing vehicle fuel emissions

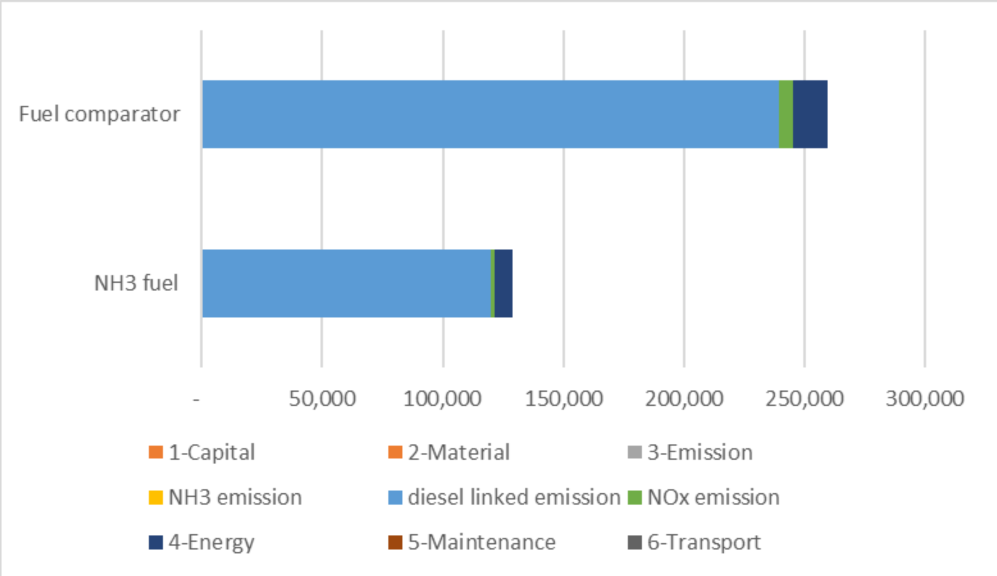
It may appear surprising that the $NH_3$ fuel produces emissions that contribute to global warming. As is discussed above this is due to 50% of the fuel's energy content being made up of diesel. Figure 6 below compares the ammonia fuel system and diesel system, breaking open the emission category. It shows that the GWP impact from emissions is solely due to the diesel content.

**Figure 6: Comparison of fuel emissions global warming potential kg $CO_2$e**




Looking at human toxicity, where ammonia and NOx emissions are likely to have a larger impact, we can see that the greatest impact is still sourced from the diesel fuel. Ammonia emissions are too small to register on Figure 7 below. However, this granular review does reveal that the ecoinvent tractor trailer process has NOx emissions greater than the regulatory ceiling used to set the limit for this study's ammonia system. This is an area that may benefit from further sensitivity.

**Figure 7: Comparison of fuel emissions acidification potential kg 1,4-DCB eq.**




## 5.1.2 Normalisation

While it is valuable to see the absolute impact of these systems across each indicator, it is important to put these impacts in to context to appreciate 'how bad' is, for instance, a kg $CO_2$ eq. compared with a kg 1,4-DCB eq.

CML publishes normalisation data for its indicators, to enable a system's impact to be compared to an average European's impact. This study has used CML normalisation data for the EU 25+3 and EU 28 population data from eurostate to derive the normalisation figures in Table 9 below.

It should be noted that even this normalisation is not entirely satisfactory, as it assumes that Europe's contribution to each environmental indicator is the same. Whilst this is not the case, the normalisation does present a reasonable and accepted way of contextualising and comparing the results.

**Table 9: Normalisation factors per environmental indicator for EU28**

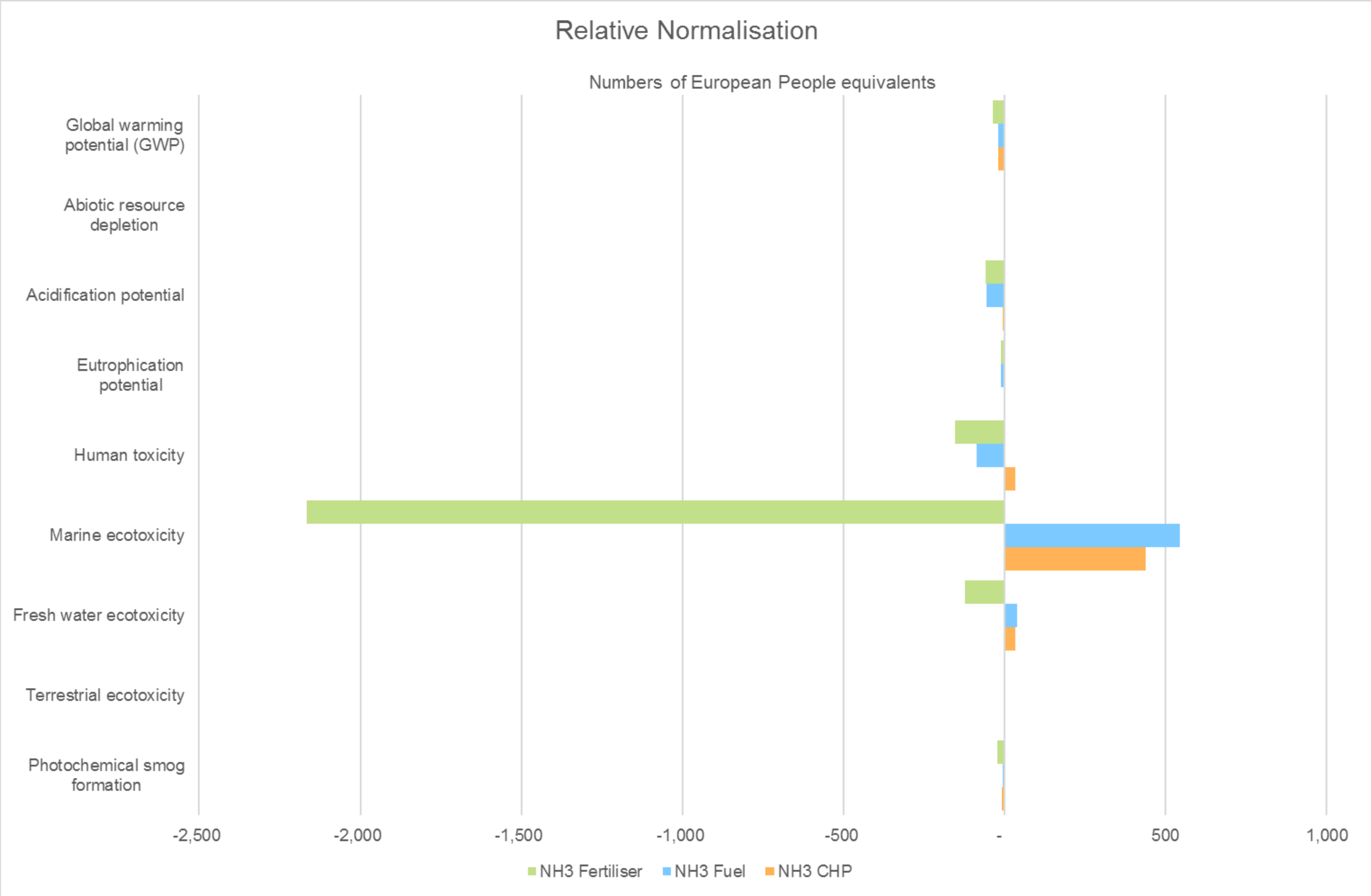
| Model Impact category | Model Unit | Total yearly emission | Average European |
|---|---|---|---|
| Global warming potential (GWP) | kg $CO_2$ eq. | 5.22E+12 | 10,719 |
| Abiotic resource depletion | kg Sb eq. | 1.62E+08 | 0.33 |
| Acidification potential | kg $SO_2$ eq. | 1.68E+10 | 35 |
| Eutrophication potential | kg $PO_4$ eq. | 1.85E+10 | 38 |
| Human toxicity | kg 1,4-DCB eq. | 5.00E+11 | 1,026 |
| Marine ecotoxicity | kg 1,4-DCB eq. | 4.47E+13 | 91,810 |
| Fresh water ecotoxicity | kg 1,4-DCB eq. | 2.09E+11 | 429 |
| Terrestrial ecotoxicity | kg 1,4-DCB eq. | 1.16E+11 | 238 |
| Photochemical smog formation | kg $C_2H_4$ eq. | 1.73E+09 | 4 |

Note: The quotient of the last two columns indicates an EU population of about 485 million.

Figure 8 below shows each system's relative impact recalibrated into units of European People Equivalents (EPEs). This has been calculated by subtracting the traditional system's impact from the ammonia system and as such, negative numbers are desired, representing a net reduction in an environmental impact.

The results are quite striking and suggest that the systems' marine ecotoxicity impact is more influential, being equivalent to many more EPEs than the other indicators. The ammonia fuel system's net marine ecotoxicity impact of 543EPEs, ammonia CHP has a net impact of 439EPEs, whereas the fertiliser scenario results in a net reduction in marine ecotoxicity of 2,000EPEs.

**Figure 8: Relative environmental impacts, normalised to numbers of European Person Equivalents (EPEs)**



The results above suggest that ammonia produced on-farm is best used to produce aqueous ammonia and offset traditional urea fertiliser. However, as is usual, the assumptions used within the processes and their life cycle stages influence the direction of the results and the relative favourability of the scenarios. For that reason, it is important to perform a careful sensitivity analysis of the key drivers.

## 5.2 Sensitivity Analysis

Due to ammonia fertiliser's strong performance over ammonia fuel and ammonia CHP, it is a strong candidate for sensitivity analysis. This is described under the headings below.

### 5.2.1 Land management and fertilisers

The initial model assesses the impact of aqueous ammonia as an alternative to urea, meeting the fertiliser needs for Spring Barley on peaty soil that is assumed to have had "*1-2 year high N leys and grazed within 2 months of ploughing 3-5 year low N leys and not grazed within 2 months of ploughing Thick permanent grass, low N*"[22]. This crop/soil/land management choice results in a requirement of 40 kg N/Ha. The following sensitivity analysis compares the impact of switching these choices to a nitrogen starved scenario and a nitrogen rich scenario. It also compares the impact of other common nitrogen fertilisers.

To model the nitrogen-starved 'worst case' option, the model assumes that spring barley is grown in sands and shallow soils with no previous management. This results in a requirement of 220 kg N/Ha. For the nitrogen-rich 'best case' option, the model assumes that spring barley is grown in peaty soils where the previous crop were not cereals and there has been "*3-5 year high N leys and grazed within 2 months of ploughing Permanent grass, high N, grazed within 2 months of ploughing*". This results in a requirement of 10kg N/Ha. These are summarised in Table 10. The model can switch between five cereal types, but this does not affect the nitrogen requirements per hectare directly; rather, some cereal types cannot be grown in certain soil types, which has an indirect effect on kg N/Ha.

**Table 10: Summary of land management options for nitrogen rich, nitrogen starved and default scenarios**

| Land management options | Nitrogen rich (best case) | Default | Nitrogen starved (worst case) |
|---|---|---|---|
| Crop (does not affect nitrogen requirements per hectare directly) | Spring Barley | Spring Barley | Spring Barley |
| Soil | Peaty soil | Peaty soil | Sands and shallow soils |

22

| Land management options | Nitrogen rich (best case) | Default | Nitrogen starved (worst case) |
|---|---|---|---|
| Previous crop | Leafy brassica vegetables, leafy non-brassica vegetables, grazed fodder, turnips grazed, brussels sprouts, cabbage (all types), calabrese (broccoli), cauliflower, kale grazed, forage rape, chicory pure stand. | Grain lupins, lettuce. | spring barley, spring oats, spring rye, spring wheat, winter barley, winter rye, winter oats, winter wheat, triticale, carrots, shopping swedes, turnips (human consumption), linseed, courgette, onions, asparagus, beetroot (red baby, other), radish, narcissus, tulip, swedes/turnips (stockfeed), parsnips, ryegrass for seeds. |
| Previous management | 3-5 year high N leys and not grazed within 2 months of ploughing 3-5 year low N leys and grazed within 2 months of ploughing Permanent grass, high N, not grazed within 2 months of ploughing | 1-2 year high N leys and grazed within 2 months of ploughing 3-5 year low N leys and not grazed within 2 months of ploughing Thick permanent grass, low N | None |
| Nitrogen requirement | 10 kg N/Ha | 40 kg N/Ha | 220 kg N/Ha |

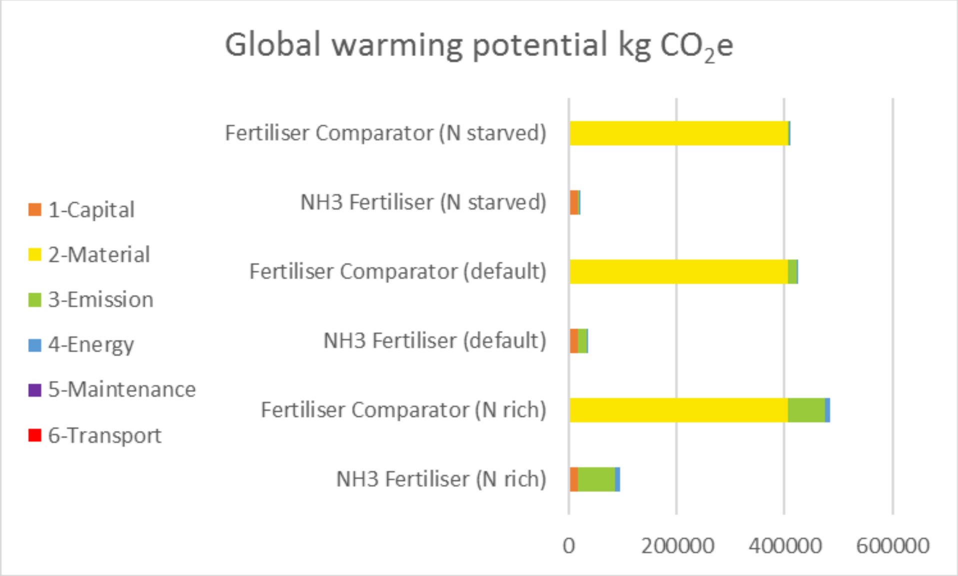
Over the course of a year, the study's farm produces ~140 tonnes of ammonia, which it converts into ~630m$^3$ of aqueous ammonia or ~570 tonnes. 1kg of aqueous ammonia contains 0.22kg of nitrogen. Using the model to switch between land management options affects the kg N/Ha requirement, impacting the number of hectares that can be treated with a years' supply of aqueous ammonia. This is summarised in Table 11 below.

**Table 11: Fertilisation potential of a years' ammonia production under different land management scenarios**

| Best case | Default | Worst case |
|---|---|---|
| 12,587 Ha | 3,147 Ha | 572 Ha |

This is an important factor to bear in mind when comparing the total impact of these systems. Since the model is designed to use all the available aqueous ammonia, improving the effectiveness of the fertiliser results in more Ha of land being fertilised, which serves to increase the emissions associated with a farm vehicle treating significantly more land. This is illustrated in Figure 9 using the global warming potential indicator as an example.

**Figure 9: Global warming potential of one year's aqueous ammonia compared with urea under different land management scenarios**



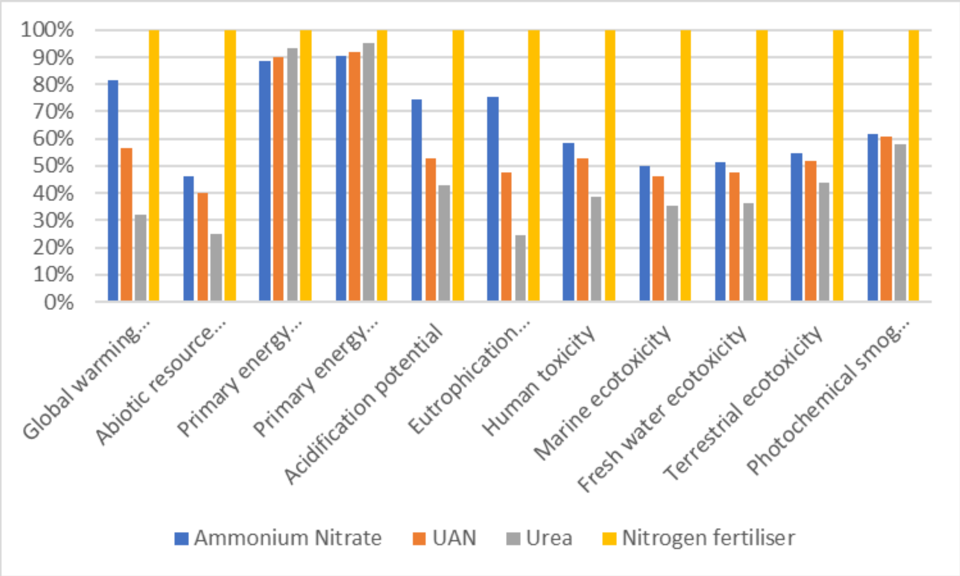

Moreover, the relative benefit of aqueous ammonia does not change under these scenarios. Since the model sources an equivalent amount of the comparator fertiliser (which can also treat more land under a nitrogen rich scenario) the net impact is the same under these different land management options. This is because the same amount of urea and aqueous ammonia is being produced in all three sensitivities and the difference between them is constant. While the emissions and capital burdens change under the different land management options, this is equal for aqueous ammonia and urea since the emissions associated with driving a tractor around a field are assumed to be identical when carrying aqueous ammonia or a comparator fertiliser. While the above is true in absolute terms, the impact per hectare does vary between the land management options. This is explored further alongside altering the fertiliser comparator in Section 5.2.1.1 below.

An interesting question for a future study would be to understand at what point aqueous ammonia will suffer from an increased transport burden at the application stage, the reasoning being that aqueous ammonia is bulkier due to being dissolved in to a large volume of water. Under nitrogen starved scenarios, there may come a point where a tractor tank cannot hold sufficient aqueous ammonia to treat a field, such that refuelling trips are required.

#### 5.2.1.1 Fertiliser comparators

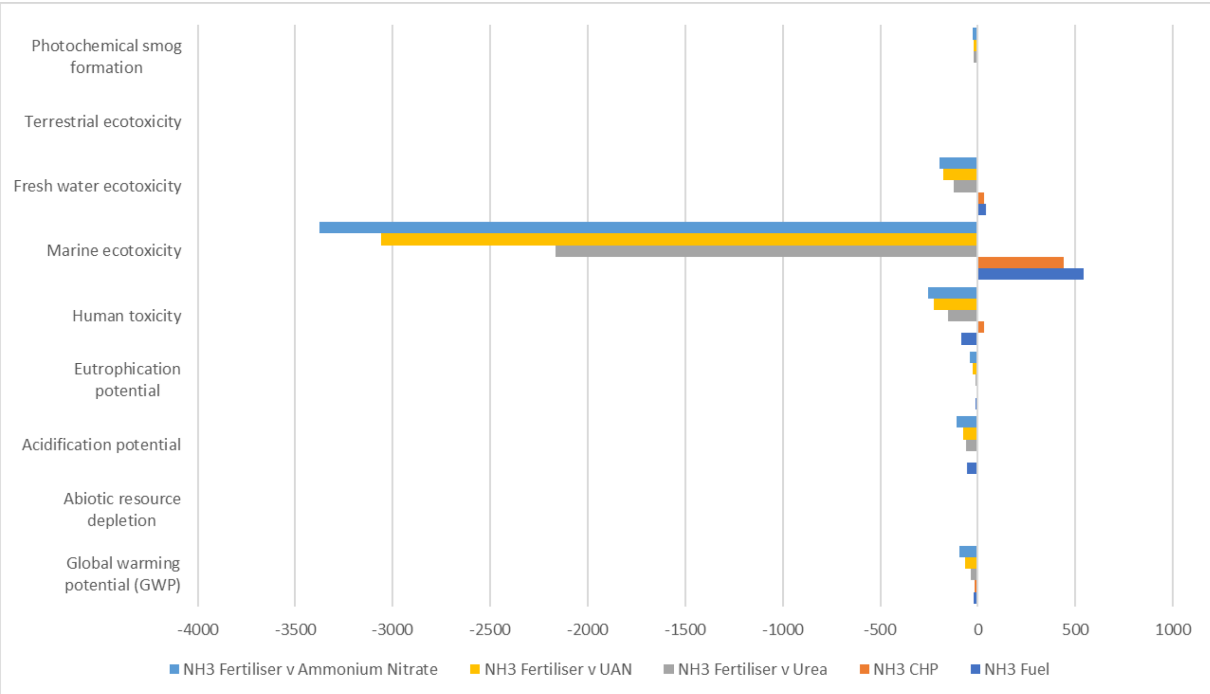
Urea is selected as the model's default comparator fertiliser, due to its common use in western Europe. This is detailed in 3.3.1 above. The model includes functionality to toggle between three other traditional fertilisers; ammonium nitrate, urea ammonium nitrate (UAN) and an ecoinvent global average for nitrogen fertilisers. The relative impacts of these fertilisers per kg of nitrogen content are shown in Figure 10 below. Urea almost always has the smallest impact, with the exception of primary energy consumption, where it consumes marginally more than ammonium nitrate and UAN.

**Figure 10: Relative impact of traditional fertilisers per kg of nitrogen**




Swapping urea out for these alternative comparators serves to increase the relative benefit of aqueous ammonia as it offsets larger impacts from UAN and ammonium nitrate. This is illustrated in Figure 11. The global average for nitrogen fertiliser is omitted from this chart since its impact dwarfs the other comparators.

**Figure 11: Relative environmental impacts, normalised to numbers of EPEs**




As mentioned previously, it is important to appreciate this impact at a year's production level and at a per hectare level. This is particularly true when changing land management options enable the study's farm to produce fertiliser with the potential to treat over 12,500 Ha. Figure 12 below compares treating one hectare of land with aqueous ammonia and each of the comparator fertilisers under the nitrogen rich, default and nitrogen starved land scenarios. Impacts are plotted (excluding ecoinvent's nitrogen fertiliser process as an outlier) as a share of the maximum impact. Lower impacts are to be expected in the nitrogen rich scenarios as less fertiliser is required to top up nitrogen levels.

There is significant variability in fertilisers' impact due to varied soil requirements. Taking global warming potential as an example, ammonium nitrate's application in a nitrogen starved environment represents the largest impact, while its application in a nitrogen rich environment is just 5% of this impact. However aqueous ammonia's application in a nitrogen starved environment is smaller still at just 2%. Figure 13 compares the relative impact of the nitrogen rich and starved soil environments to enable a clearer comparison between fertiliser types.

**Figure 12: Relative impact of fertilisers in different soil environments**

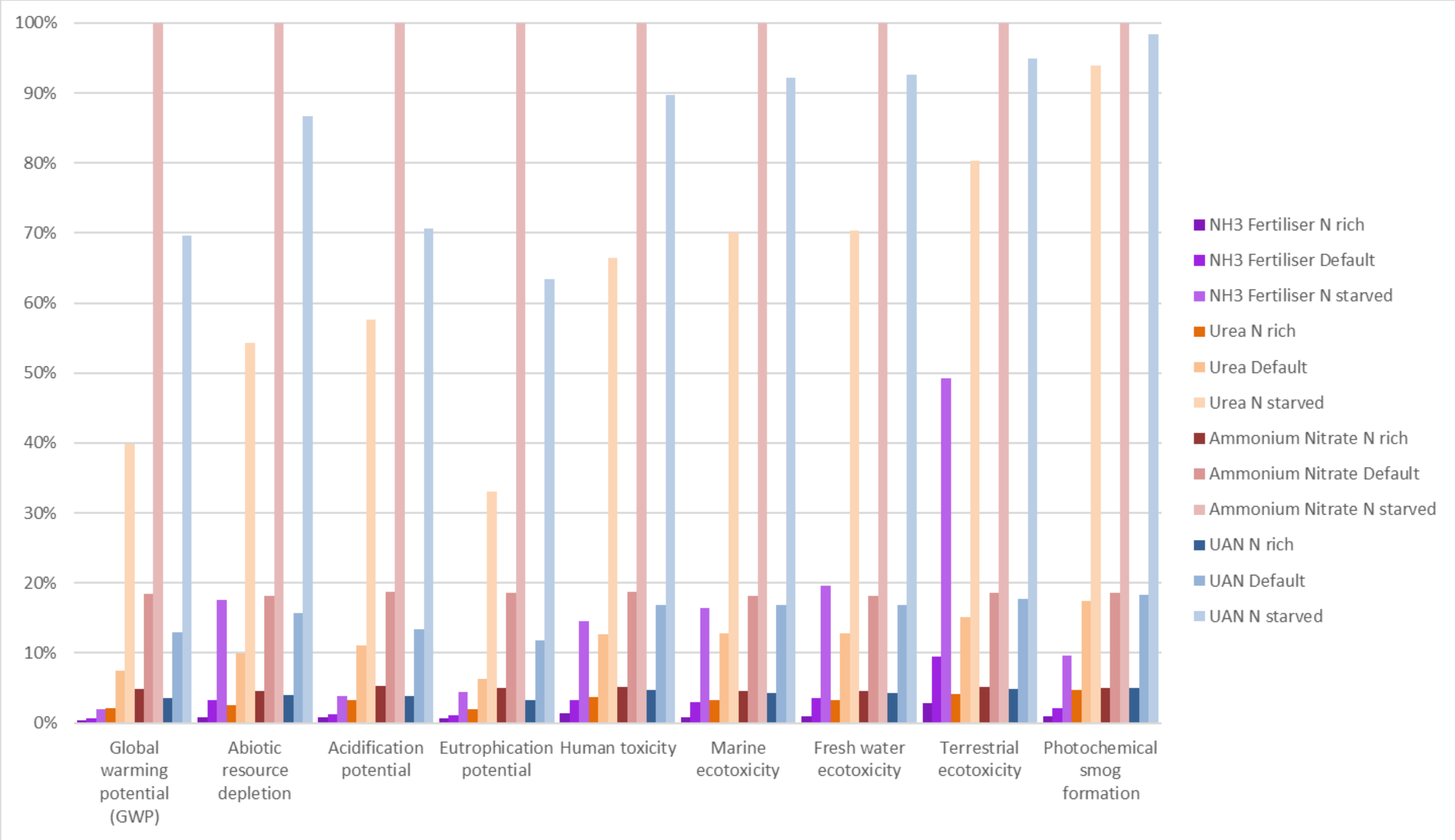
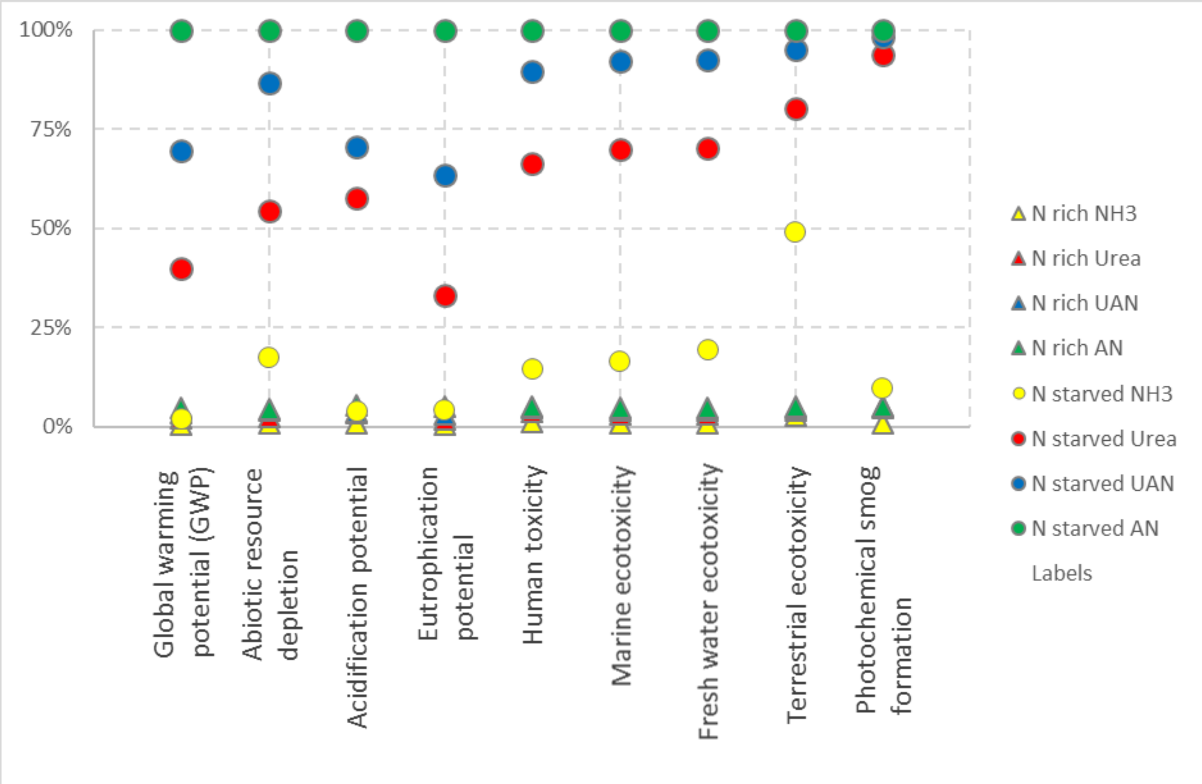


**Figure 13: Relative impact of fertilisers in nitrogen rich and nitrogen starved soil environments**




In the initial model we saw that the farmer's best option was to use aqueous ammonia and avoid using urea. Swapping urea for alternative fertiliser products only serves to increase this benefit, to the extent that aqueous ammonia applied in nitrogen starved soils has a smaller or equal impact to comparators applied in nitrogen rich soils.

The study's farm is 200 Ha in size. Assuming fertiliser is applied twice per year and that a farmer will want to have a 25% contingency, the farm can be assumed to have a fertiliser need of ~450 Ha per year. As we can see from Table 11, under favourable conditions a farmer could produce as much as 27 times their annual need. A question therefore arises: is it better to produce 450 Ha worth of aqueous ammonia and then meet the farm's fuel and CHP needs? Or is it better to make only aqueous ammonia and then export this to other farms?

### 5.2.2 Fertiliser export

This sensitivity examines producing enough aqueous ammonia to treat the farm's 450 Ha requirement per year and then compares using the remainder for CHP and fuel or fertiliser exports to other farms. The goal of the export sensitivity analysis is to understand how far away neighbouring farms need to be before ammonia export has the larger impact.

For the purposes of this sensitivity, a hypothetical farm profile has been built using SRUC data per tonne of grain[23]. This is shown in Table 12 below.

**Table 12: Farm profile**

| | Fertiliser need per annum | Tractor need per annum | Energy need per annum |
|---|---|---|---|

[23] based on average figures collected to December 2017 via AgREcalc SAC's Carbon Footprinting tool used by the Farm Advisory Service, Scotland.

| | | | |
|---|---|---|---|
| System requirement | 450 Ha | 503.91 ktkm | 22.47 MWh |
| $NH_3$ requirement | 20t | 25t | 10t |

To deliver this profile, 55 tonnes of ammonia are required per year. The study's farm produces 143 tonnes per annum (or 2.6 Farm Years) which leaves 88 tonnes of excess ammonia supply. As the farm has no need for these 88 tonnes of ammonia, it is assumed that they will certainly be sent elsewhere. Therefore, this sensitivity explores using the 35 tonnes of ammonia required for the farm's tractor and energy needs, for fertiliser export.

Additionally, given fertiliser's greater environmental benefits, it is assumed that the ammonia facility is built for fertiliser production and its use for CHP and vehicle fuel would be a by-product of the main process. Capital burdens have therefore been removed from this assessment to understand the benefits of using ammonia for CHP and vehicle fuel or fertiliser export after the main need is met. The system requirements are set out in Table 13.

**Table 13: Summary of system requirements**

| | No export | Export | Status quo |
|---|---|---|---|
| Farm's fertiliser need | 20 t $NH_3$ | 20 t $NH_3$ | 18 t Urea |
| Farm's tractor need | 25 t $NH_3$ | 22 t Diesel | 22 t Diesel |
| Farm's energy need | 10 t $NH_3$ | 4,605 $m^3$ Natural gas | 4,605 $m^3$ Natural gas |
| Export fertiliser | - | 35 t $NH_3$ | - |

The export scenario consists of the core $NH_3$ fertiliser system, the counterfactual tractor trailer, the counterfactual CHP system and an additional $NH_3$ 'export' fertiliser system. This export system uses the 35 tonnes of ammonia diverted from the $NH_3$ CHP and Fuel systems to produce aqueous ammonia and is then charged with a transport burden. Traditional fertiliser use is still offset through the export system.

Table 14 below, shows the relative normalised impacts of the 'no export', 'export' and status quo scenarios. Negative numbers (in blue) are desired and represent a net reduction in the given impact category. The export and no export scenarios both lead to net reductions across the environmental criteria.

**Table 14: Relative impact of different scenarios, reported in units of EPEs**

| Indicator | No export | Export (10 mile) | Status quo |
|---|---|---|---|
| Marine ecotoxicity | -438 | **-1,000** | 465 |
| Fresh water ecotoxicity | -26.5 | **-61.4** | 28.1 |
| Human toxicity | **-50.7** | -29.9 | 74.4 |
| Acidification potential | **-19.8** | -7.82 | 25.9 |
| Global warming potential (GWP) | **-10.4** | -5.84 | 14.3 |
| Photochemical smog formation | -5.71 | **-5.95** | 7.28 |
| Eutrophication potential | **-4.23** | -1.78 | 5.46 |
| Abiotic resource depletion | -0.87 | **-2.28** | 0.883 |

| | | | |
|---|---|---|---|
| Terrestrial ecotoxicity | -0.38 | **-0.79** | 0.431 |

In this case where the export destination is 10 miles from the original farm, not exporting the ammonia is already preferable for four of the environmental indicators, namely global warming potential, acidification potential, eutrophication potential and human toxicity. As the destination gets even further away, the increasing transport burden leads to the 'no export' scenario being preferred across all indicators. The tipping points for the remaining indicators are shown in Table 15 and Figure 14 below.

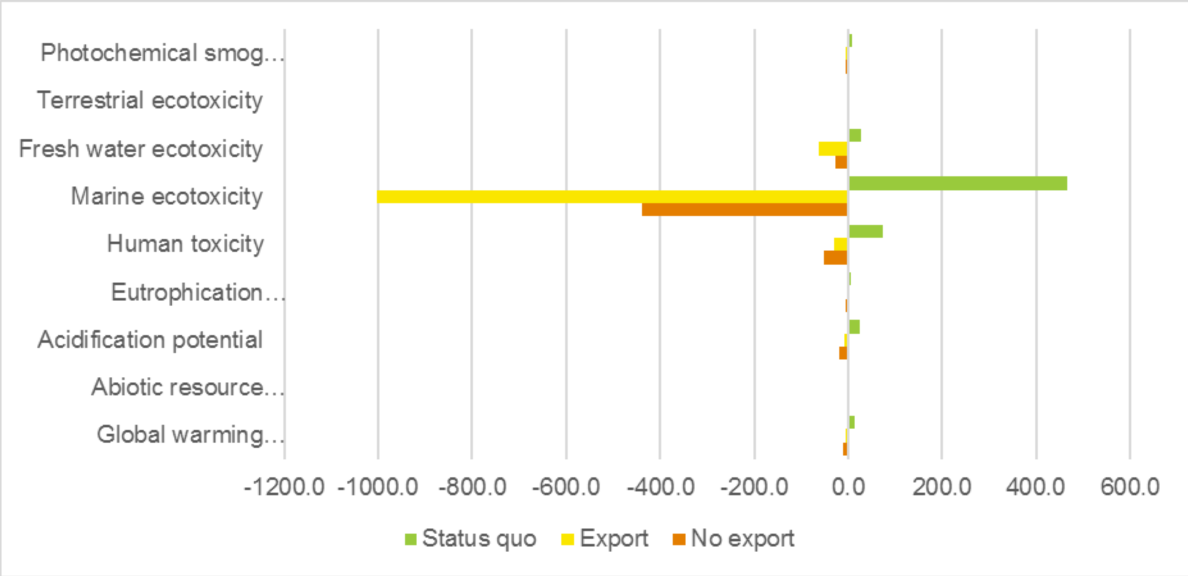
**Table 15: Summary of export distances required to overly burden ammonia export**

| Abiotic resource depletion | Marine ecotoxicity | Fresh water ecotoxicity | Terrestrial ecotoxicity | Photochemical smog formation |
|---|---|---|---|---|
| 1,648 miles | 420 miles | 829 miles | 675 miles | 61 miles |

**Figure 14:Export distances required to overly burden ammonia export**


With the exception of photochemical smog formation, the indicated distances are all further than the longest distance between places on mainland Scotland, indicating that these results are relatively unsensitive to the location of the destination farm. Arguably, the key indicator is marine ecotoxicity. This criterion has the largest difference between the scenarios, with impacts in the hundreds of EPEs. This is illustrated in Figure 15.

**Figure 15: Relative impact of different scenarios, reported in units of EPEs**




While the ‘no export’ scenario can deliver larger benefits across some indicators in a 10-mile scenario, on the key indicator (marine ecotoxicity), the export scenario it delivers a benefit that is over two times larger, offsetting the impact of ~1,000EPEs.

## 5.3 Recommendations for future studies

This study’s results suggest that a farmer’s best option is to use ammonia to produce aqueous ammonia fertiliser and export any leftovers to neighbouring farms. However, it would be interesting to test this finding further. The following headings set out this report’s recommendations for future studies.

### 5.3.1 Renewable burden

The analysis within this report assumes that the synthesis process receives its electricity burden free. It would add robustness to these results to account for the impacts of constructing the wind turbine or another form of renewable energy. This would also lend itself to running this assessment in other locations where solar energy may be preferable.

### 5.3.2 Water scarcity

This study does not assess the system’s water footprint. However, large volumes of water are consumed in the hydrogen electrolysis and aqueous ammonia stages. While water scarcity is not an acute issue in Scotland (the location of this farm’s study), this may not be the case in other parts of the world. If there is a desire to use these results to understand the impact of developing a similar system in the developing world it may be useful to understand its impact on local water scarcity.

### 5.3.3 Aqueous ammonia refuelling burden

This study assumes that the application of traditional fertilisers and aqueous ammonia are the same in terms of environmental impact. However as identified in the land management and fertilisers sensitivity, in nitrogen starved environments, significantly more fertiliser is required. Given the bulky nature of aqueous ammonia, this may have impacts on how much land a tractor can treat without refilling the ammonia tank. An addendum to the land management and fertiliser sensitivity could explore what volume of aqueous ammonia can be held in a tractor’s tank and calculate refuelling trips per hectare in a nitrogen starved scenario.

### 5.3.4 Ammonia engine efficiency

As described in the system specification, the emission profile for the ammonia engine is set at regulatory limits for $NO_x$ and $NH_3$. These are predicated on the engine's efficiency. A further sensitivity that explores the impact of more efficient and cleaner engines would provide useful insights, particularly when determining what to do with fertiliser once a farm's own fertiliser need has been met.

### 5.3.5 Ammonia fuel cell

A further study that assesses the impact of an on-vehicle ammonia fuel cell would provide insights with similar benefits to the above. This system was rejected as a candidate for the tractor fuel in this study since it requires significant modification to the tractor. However, it would remove the need for a co-fuel removing all the emissions associated with diesel that adversely impact the tractor fuel system. On-vehicle cracking of ammonia is at a relatively low technology readiness level and stakeholder interviews would be needed to provide confidence in the system's design.

### 5.3.6 Tractor emission

Analysis of the source of specific emissions within the ammonia and comparator vehicle fuel systems revealed that the ecoinvent process for tractor trailer has higher NOx emissions than the regulatory ceiling. A further study looking in more detail at an ammonia engine's $NH_3$ and NOx emissions would provide more evidence to understand whether the regulatory limits are too generous for an ammonia system.

# 6 Conclusion

Aqueous ammonia fertiliser is found to provide the largest environmental benefit out of the three ammonia uses assessed. It is responsible for a smaller environmental impact than its urea comparator across each environmental criterion. The ammonia vehicle fuel and ammonia CHP systems analysed deliver environmental benefits across many indicators, including global warming potential, however the diesel fuel and natural gas CHP comparators were found to deliver smaller environmental impacts on criteria such as human toxicity, marine ecotoxicity and freshwater ecotoxicity.

Contextualising the systems' environmental impact in terms of EPE suggests that marine ecotoxicity is the key indicator, since its impact amounts to many more EPEs than the other indicators.

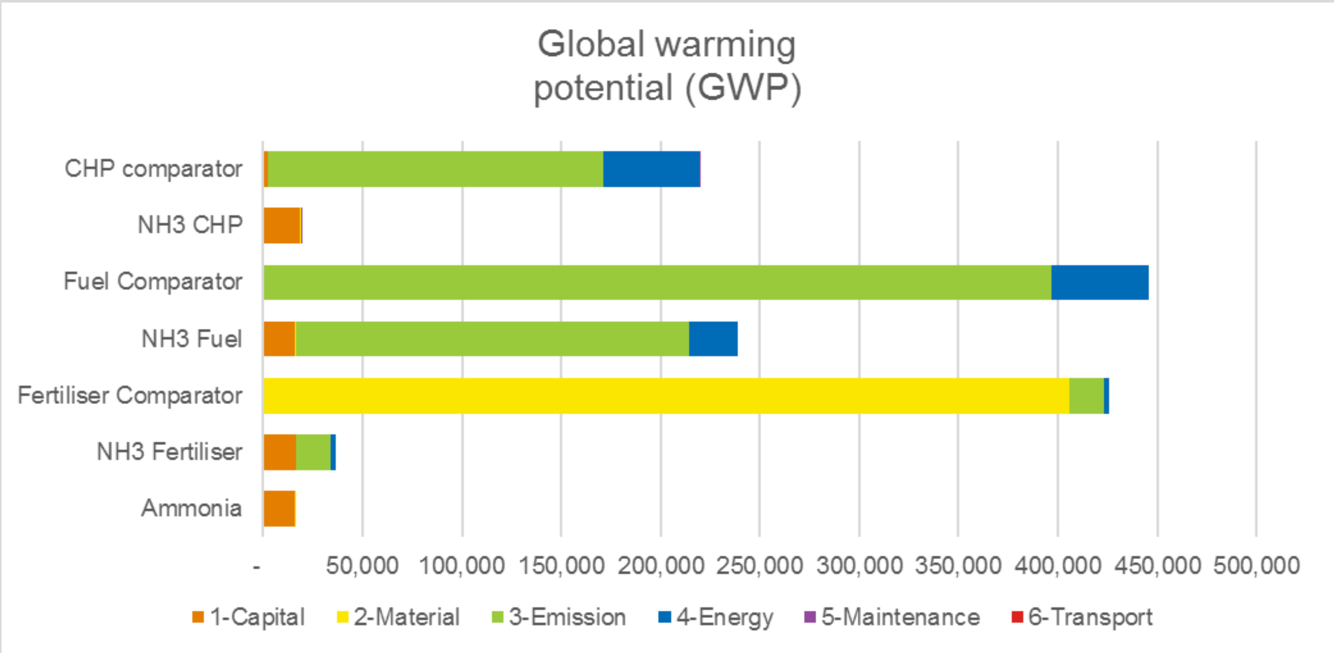
Sensitivity analysis into soil type and land management options reveals that there is significant variability in fertilisers' environmental impact due to varying soil requirements. However, aqueous ammonia is found to always have the smallest impact when compared to urea, ammonium nitrate and UAN. Moreover, its impact in a nitrogen starved environment is found to have equal or smaller impacts than other fertilisers' use in a nitrogen rich environment.

The study's farm is found to have ammonia production capacity that exceeds its fertiliser need. Sensitivity analysis into using this excess ammonia to produce further fertiliser for export is compared with using it to meet the farm's vehicle and heat & power needs. Both systems are found to deliver net environmental benefits when compared to the traditional comparators. The no export scenario is found to deliver the largest benefit across indicators such as global warming potential, acidification potential, eutrophication potential and human toxicity. However, it is this study's conclusion that the export scenario is preferred since it delivers a marine ecotoxicity benefit equivalent to -1,000EPEs compared to -438EPEs in the no export scenario. A transport burden greater than the length of Scotland is required for the no export scenario to deliver a larger marine ecotoxicity benefit.

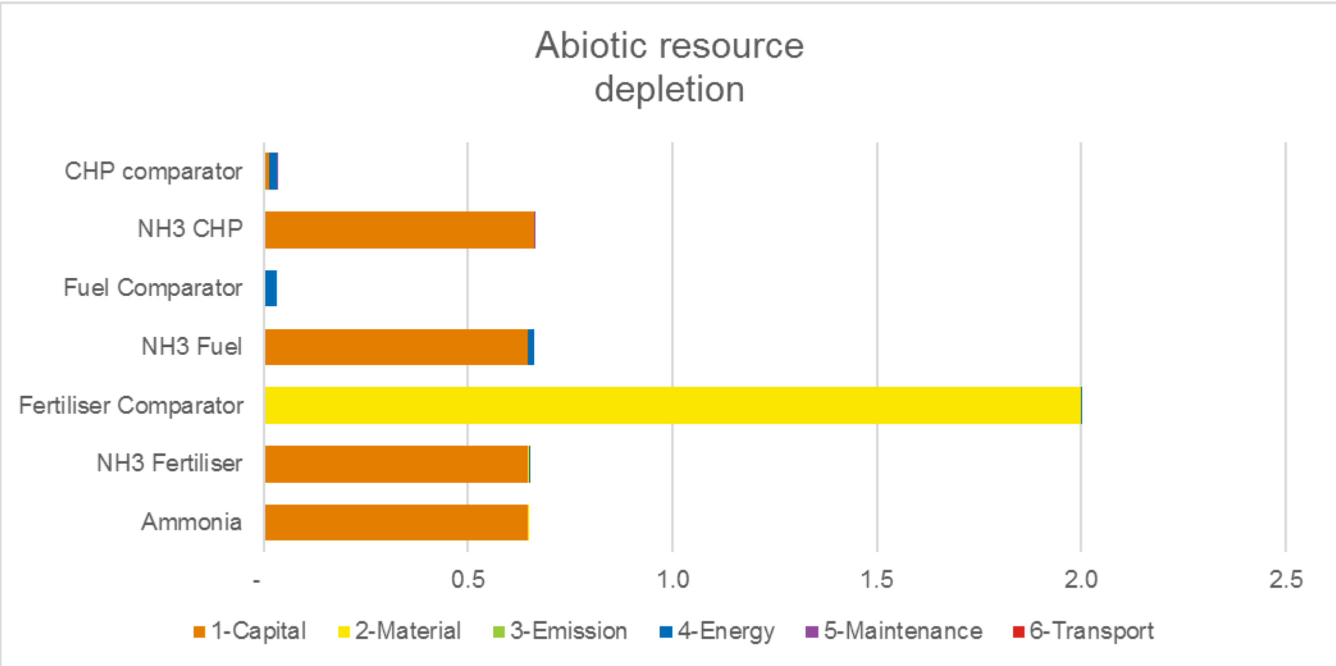
# Appendices

# Appendix 1 - System impacts per year's ammonia production

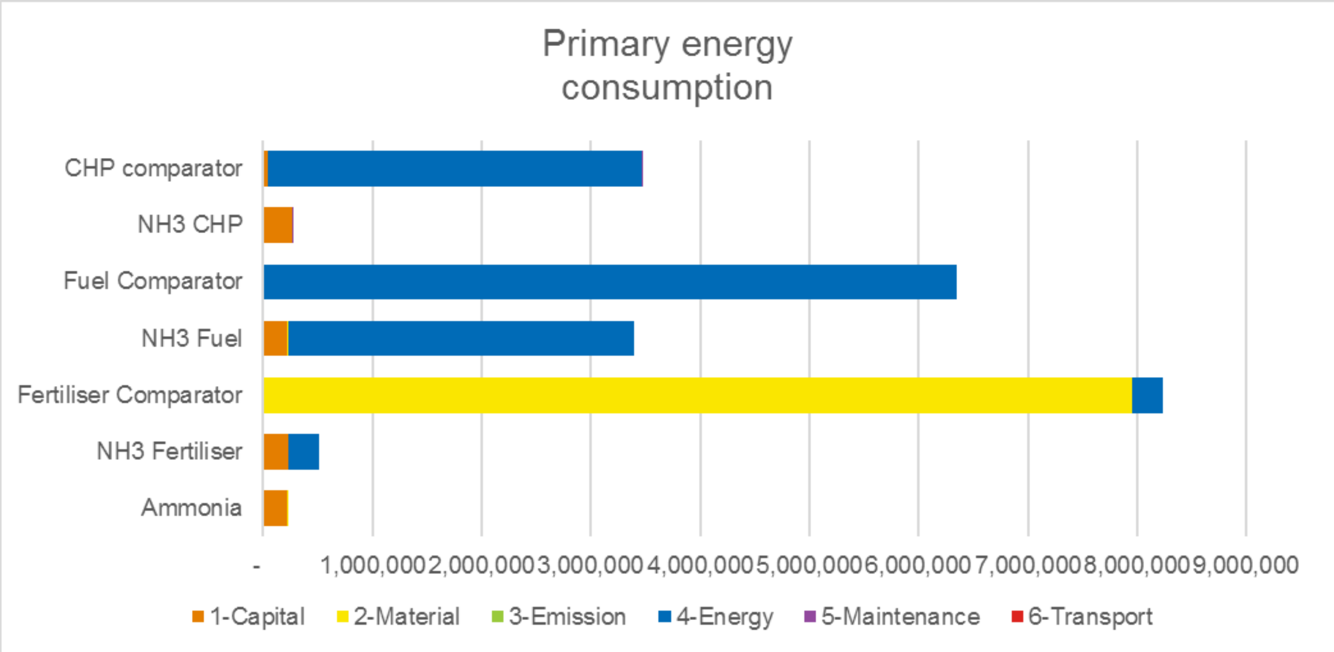
Global Warming Potential (kg $CO_2e$) per year's ammonia production



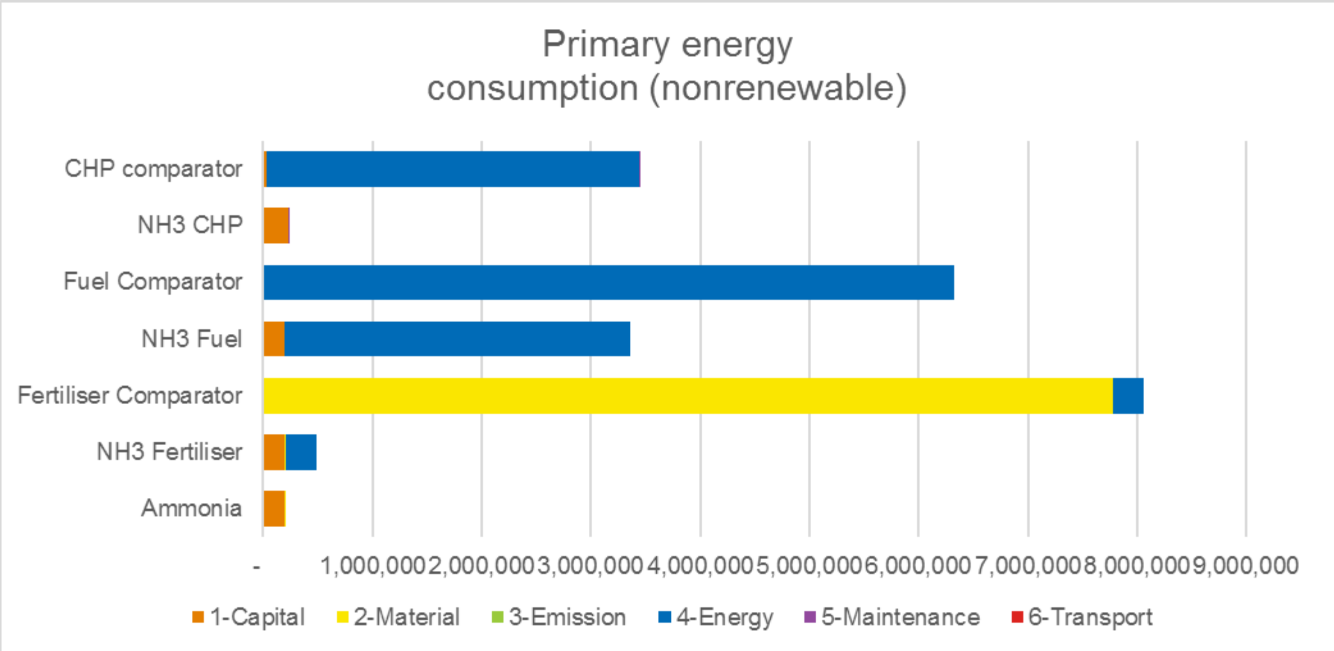

Abiotic Resource Depletion (kg Sb eq) per year's ammonia production



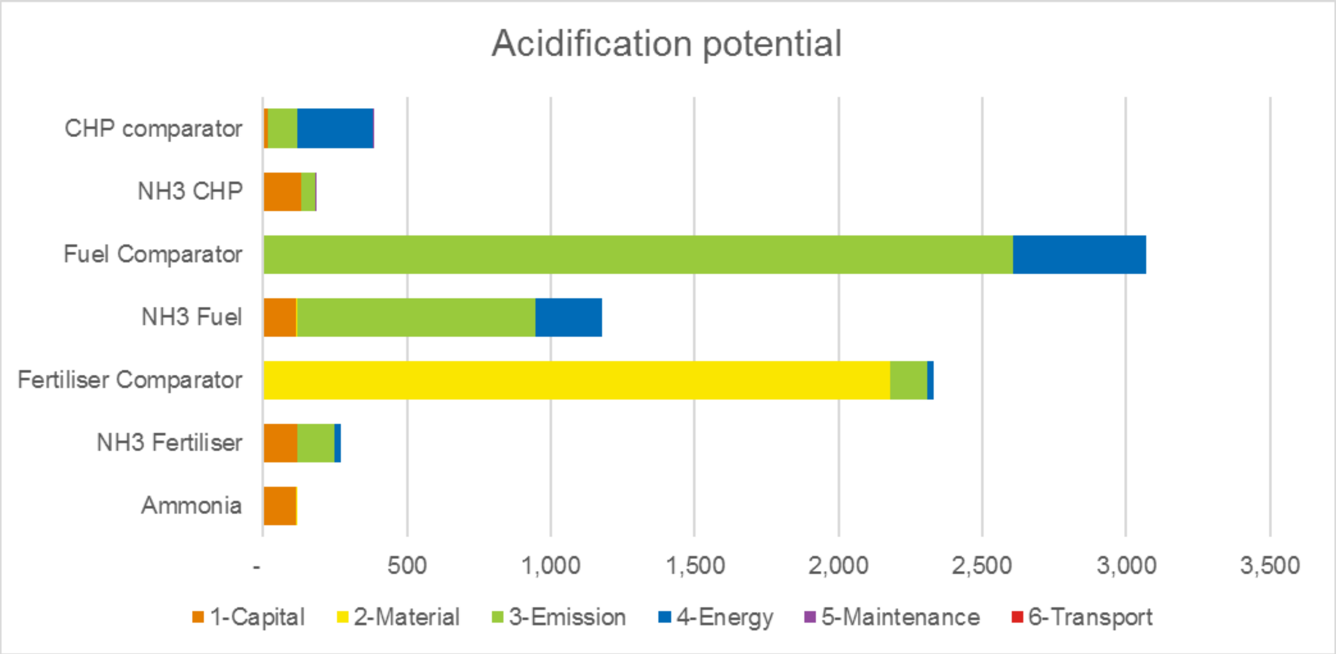

Primary energy consumption – (MJ) per year's ammonia production



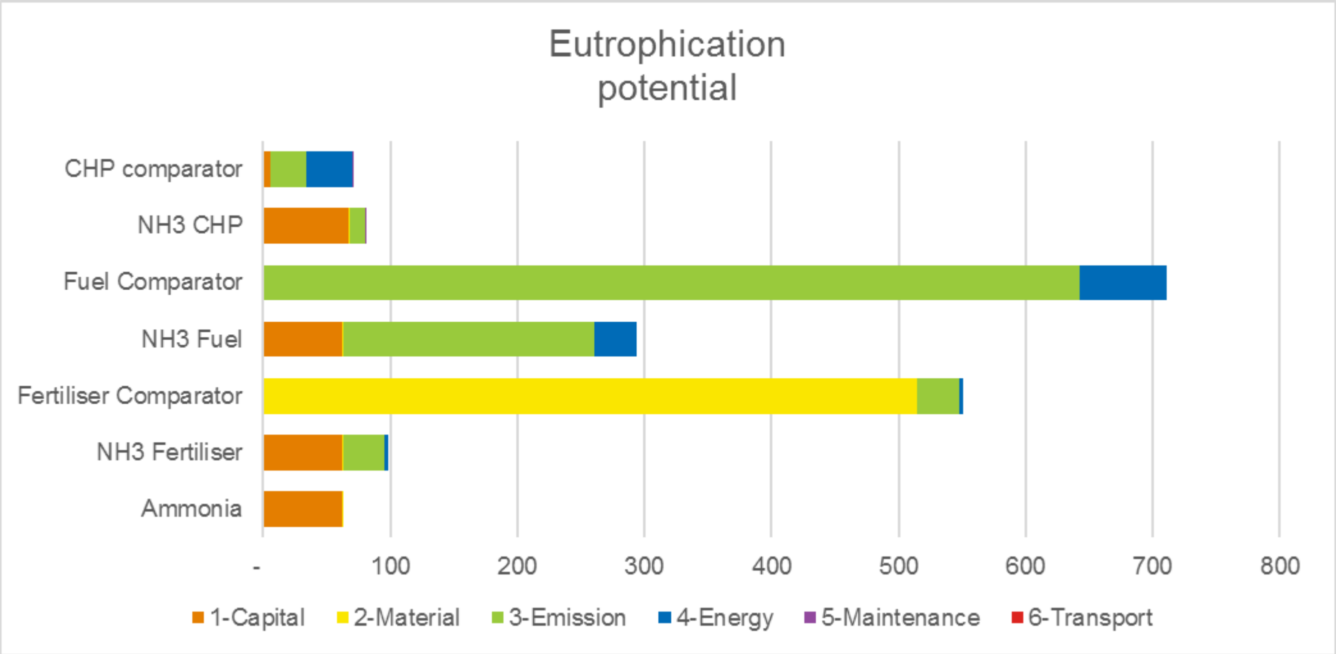

Primary energy consumption – non-renewable (MJ) per year's ammonia production



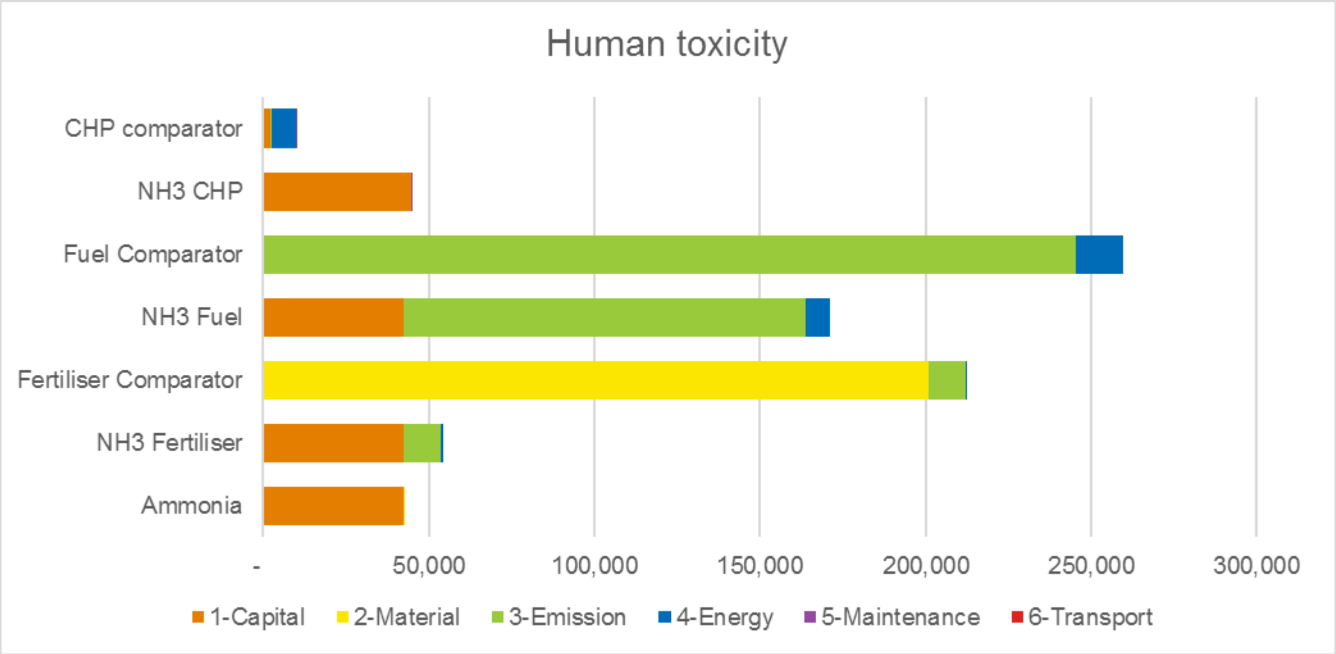

Acidification Potential (kg $SO_2e$) per year's ammonia production



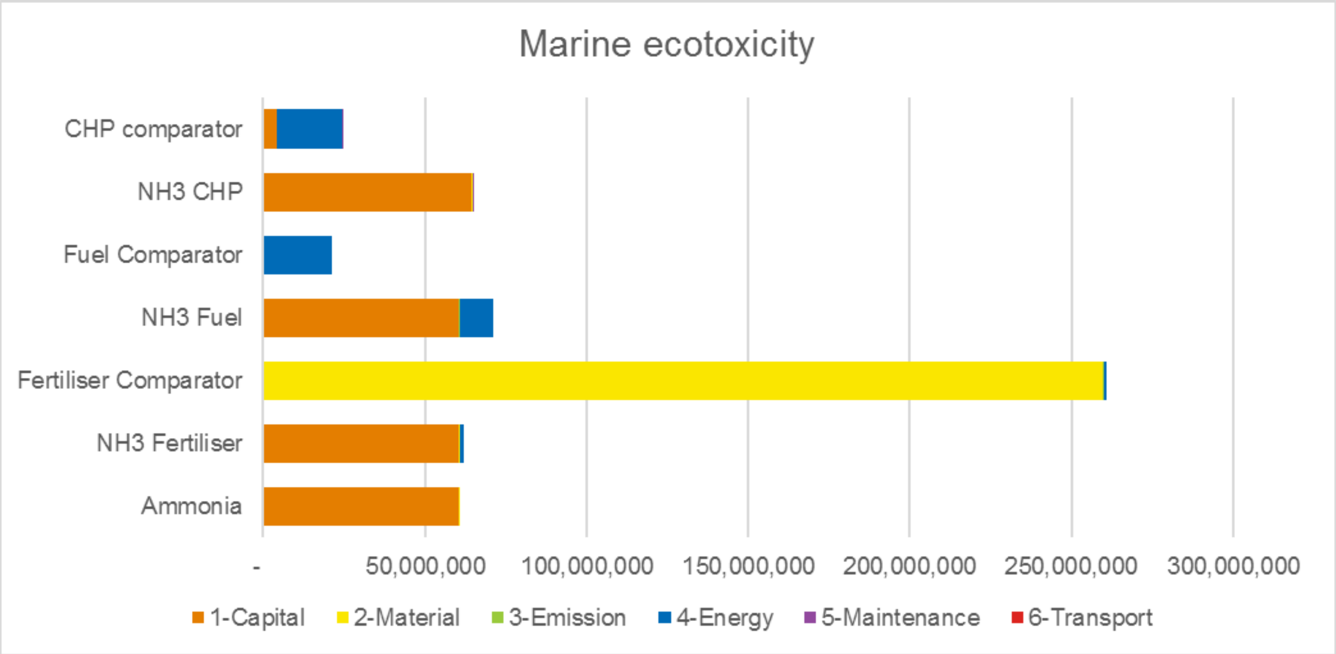

Eutrophication Potential (kg $CO_4e$) per year's ammonia production



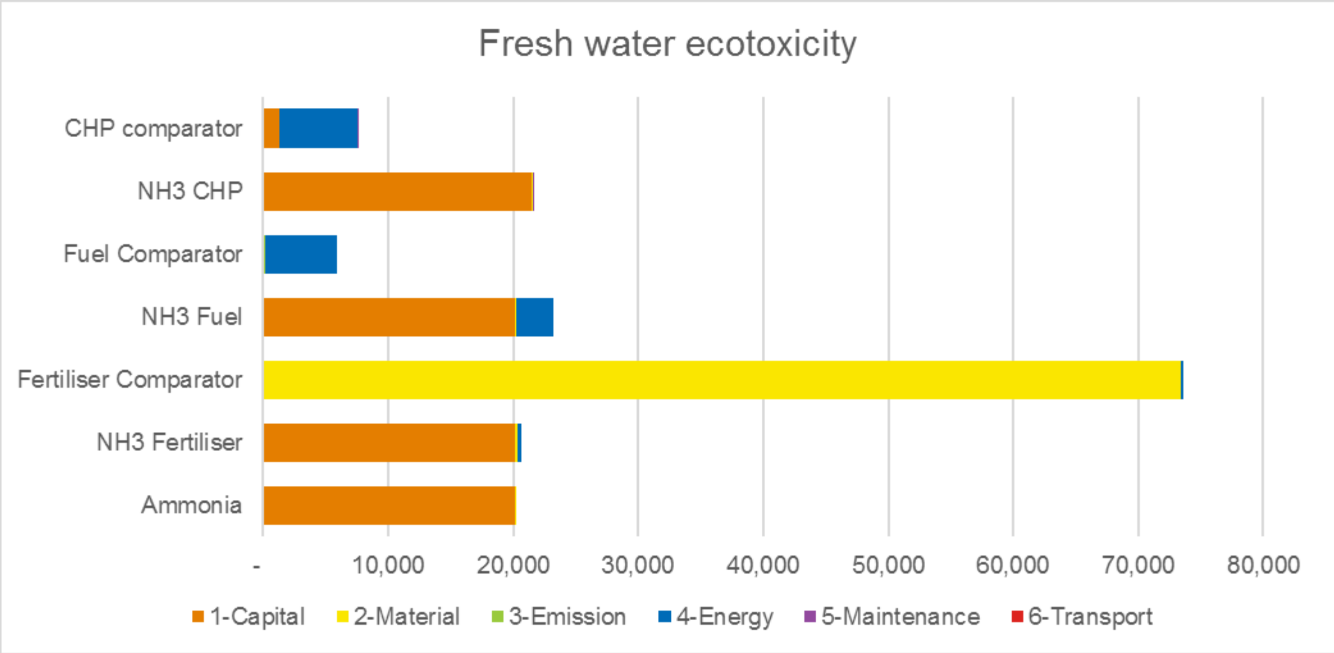

Human toxicity (kg 1,4-DCBe) per year's ammonia production



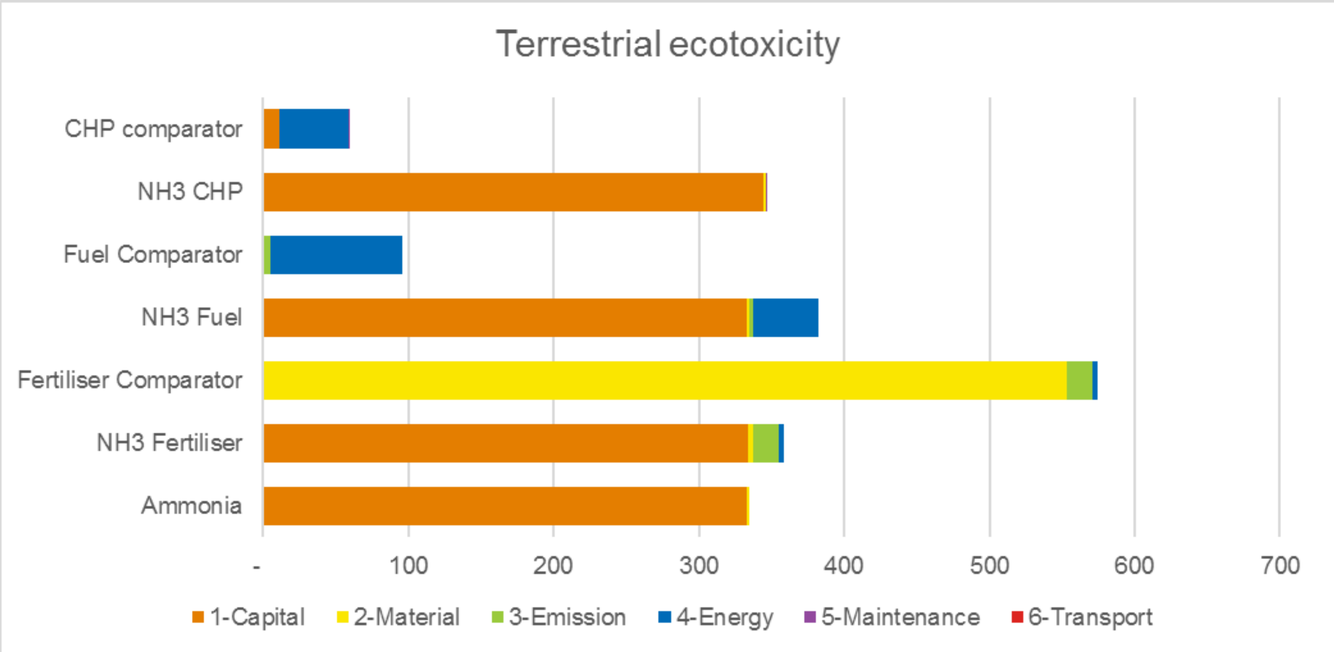

Marine ecotoxicity (kg 1,4-DCBe) per year's ammonia production



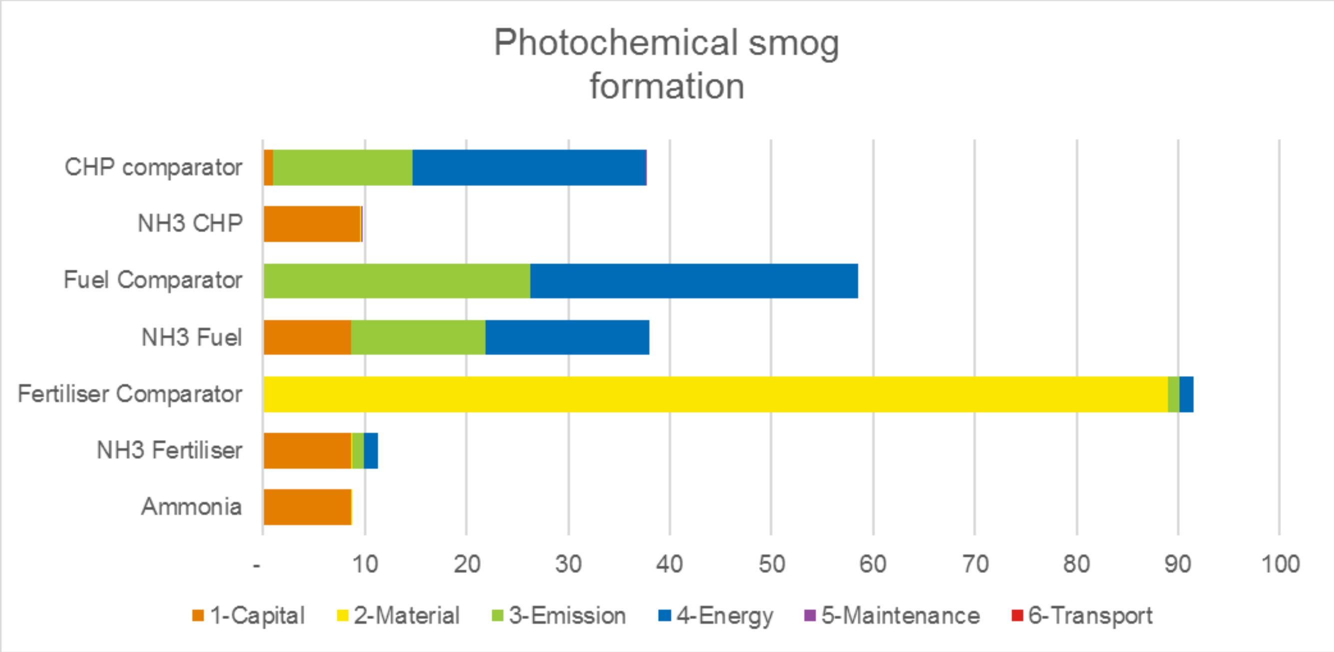

Fresh water ecotoxicity (kg 1,4-DCBe) per year's ammonia production




Terrestrial ecotoxicity (kg 1,4-DCBe) per year's ammonia production




Photochemical Smog Formation (kg $C_2H_4e$) per year's ammonia production


Photochemical smog formation
CHP comparator
NH3 CHP
Fuel Comparator
NH3 Fuel
Fertiliser Comparator
NH3 Fertiliser
Ammonia
-
10
20
30
40
50
60
70
80
90
100
1-Capital
2-Material
3-Emission
4-Energy
5-Maintenance
6-Transport

# Appendix 2 – QA Audit table

| ID | Table | Entries | Likely Error | Potential error | Not Best Practice | Reviewed / Checked | Question | Unchecked | Same As Previous |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Index_Log | 22 | 0 (0) | 0 (1) | 1 (1) | 15 (14) | 0 (0) | 6 (6) | 0 (0) |
| 2 | Contents_Log | 38 | 0 (0) | 0 (3) | 1 (2) | 4 (0) | 0 (0) | 33 (33) | 0 (0) |
| 3 | Formula_Log | 2722 | 0 (0) | 0 (5) | 58 (67) | 619 (600) | 0 (5) | 0 (0) | 2045 (2045) |
| 4 | Errors_Log | 333 | 0 (0) | 0 (1) | 235 (235) | 5 (4) | 0 (0) | 0 (0) | 93 (93) |
| 5 | Names_Log | 184 | 0 (1) | 0 (21) | 40 (42) | 144 (120) | 0 (0) | 0 (0) | 0 (0) |
| 6 | Comments_Log | 102 | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 101 (101) |
| 7 | Links_Log | 0 | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| 8 | References_Log | 37 | 0 (0) | 0 (0) | 0 (0) | 36 (36) | 0 (0) | 1 (1) | 0 (0) |
| 9 | Objects_Log | 59 | 0 (0) | 0 (0) | 1 (1) | 58 (58) | 0 (0) | 0 (0) | 0 (0) |
| 10 | Validations_Log | 2867 | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 2866 (2866) |
| 11 | Conditions_Log | 75 | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 74 (74) |
| 12 | Modules_Log | 0 | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| 13 | Procedures_Log | 0 | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| | **Totals** | **6439** | **0** | **0** | **336** | **884** | **0** | **40** | **5179** |

The QA audit reviewed over 6,400 unique formulae within the model. 32 formulae were flagged for further checking. These issues consisted of obsolete named ranges, superfluous calculations, and a hard-coded value. The redundant formulae and named ranges were removed and the hard-coded value was corrected. Several “not best practice” errors were identified that related to the model correctly returning a value error when it could not source CED characterisation factors. These were checked to function correctly. Other “not best practice” values and questions issues related to hard coded values or formulae within raw data. These values were checked and explanation provided.

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