Building an LCA Inventory:

A Worked Example on a CO_2 to Fertilizer Process

Technische Universität Berlin

RWTH AACHEN UNIVERSITY

The University Of Sheffield.

IASS POTSDAM

SUPPORTED BY

GLOBAL CO_2 INITIATIVE
UNIVERSITY OF MICHIGAN

eit Climate-KIC

Climate-KIC is supported by the EIT, a body of the European Union

Published April 2020
This work is available under DOI 10.3998/2027.42/154989
and can be downloaded via http://hdl.handle.net/2027.42/154989

Main Contributors

The University of Sheffield
Ana Villa Zaragoza
Stephen McCord
Peter Styring

Further Contributions

Institute for Advanced Sustainability Studies e.V. Potsdam
Lorenzo Cremonese
Till Strunge

Global CO_2 Initiative
Volker Sick

SUPPORTED BY

Climate-KIC is supported by the EIT, a body of the European Union

Foreword

Climate change is one of the largest challenges of our time. It is proven that excess amounts of carbon dioxide that humanity has added to the atmosphere plays a key role, and left unaddressed, this will alter ecosystems and fundamentally change life as we know it. Under the auspices of the UN Framework Convention on Climate Change and through the Paris Agreement, there is a commitment to keep global temperature increase to well below two degrees Celsius. Meeting this goal will require a variety of strategies including increased renewable power generation and broad scale electrification, increased energy efficiency, and carbon-negative technologies. Carbon-negative technologies serve two purposes, as a climate mitigation tool near term, and to create a new carbon economy that recycles carbon over the long term- balancing emissions of still essential industrial sectors such as cement and steel. Overall, carbon-negative technologies are a valuable strategy in an overall portfolio of approaches to stabilize the atmospheric carbon dioxide concentration at a level that supports human life on Earth.

Increased attention is being paid to the notion that carbon dioxide can become a valuable resource instead of being a waste product with severe negative consequences to the earth's climate. New technologies, new use cases, interest from the investment community, and growing legislative support poise the use of a carbon dioxide feedstock as a viable economic and societal opportunity.

But not all that glitters is gold! Thorough assessment of the environmental and economic benefits of new technologies is paramount prior to deployment. Transparent and consistent life cycle assessments and techno-economic assessments must provide unbiased information to decision makers to enable sound decisions on investments, deployments, and public support for such.

International demand from government bodies, industry, investors, non-profits, and researchers for harmonized approaches to conduct life cycle assessments and techno-economic assessments for carbon dioxide utilization led us to coordinate and fund an international effort to develop and disseminate Guidelines for TEA & LCA for CO_2 Utilization. First published in 2018, these Guidelines have found widespread attention and use. A growing list of case studies, and worked examples, is made available to illustrate how to use these Guidelines.

We hope that this case study will be useful to you and we will be grateful for any feedback!

Abbreviations

ADP: Abiotic depletion potential

AP: Acidification potential

EP: Eutrophication potential

FAETP: Freshwater aquatic ecotoxicity potential

GHG: Greenhouse gases

GWP: Global warming potential

HTP Human toxicity potential

LCA: Life cycle assessment

LCI: Life cycle inventory

LCIA: Life cycle impact assessment

MAETP: Marine aquatic ecotoxicity potential

NPK: Nitrogen, phosphorus, potassium

POCP: Photochemical ozone creation potential

ODP: Ozone layer depletion potential

TETP: Terrestic ecotoxicity potential

TRL: Technology readiness level

This worked example is part of a series of worked examples produced in support of the "Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization". These guidelines, further worked examples and other associated documents can be found online at:

https://deepblue.lib.umich.edu/handle/2027.42/145423

More details on the Global CO_2 initiative can be found online at:

https://www.globalco2initiative.org/

***This worked example can be read independently of or in conjunction with:**

"Interpretation of LCA results: A worked example on a CO_2 to fertilizer process"

Contents

1. Introduction

The Techno economic assessment & life cycle assessment guidelines for CO_2 utilization were published in 2018 (Zimmermann, et al., 2018). Alongside this, life cycle assessment (LCA) worked examples have also been produced to show the application of these guidelines to practical cases. Each worked example highlights specific facets of the guidelines by sharing notes, tips and suggestions on how to address the challenges of building a LCA for CO_2 utilization. This worked example draws attention to the life cycle inventory and impact assessment phase and the challenges of collecting/selecting data. To arrive at this point, the first steps in LCA construction are also considered, this includes: setting a goal and a scope for the study; determining system boundaries; identifying limitations; solving multifunctionality and identifying data quality issues. Notes with suggestions for conducting all parts of the LCA before arriving to life cycle inventory are also given in this worked example. The main goal of this work is to be used as a teaching example that illustrates LCA construction and should not be considered as an actual LCA study with results that can be used for public or private comparisons. The product under assessment is a CO_2 based fertilizer that uses carbon dioxide captured from a power generating facility. Field trials have suggested that the compound costs, looks and spreads the same as common fertilizers such as ammonium nitrate, all of these are adjudged to be important factors for marketing perspectives. Other potential benefits include water and nutrient retention, soil carbon replenishment, raising pH and temperature of the soil and boosting microbial activity. Whilst there is preliminary information on the potential environmental benefits of using this CO_2 based fertilizer, there is no full LCA study available yet.

World consumption of fertilizer is mainly driven by three fertilizer nutrients, nitrogen, phosphate and potassium (in the form of potash). The FAO estimated in its 2020 world fertilizer trends and outlook report that fertilizer consumption reached 186.67 million tonnes in 2016 and was forecast to grow annually on average by 1.5% (N), 2.2% (P) and 2.4% (K) from 2015 to 2020 (FAO, 2017). In Europe: France, Germany and the UK represent 40 % of the fertilizer market which equals 10 % of the total use at global level in volume, with nitrogen being the most used nutrient in the EU by volume. Fertilizer Europe estimates that 75% of the cultivated agricultural land (Fertilizers Europe, 2000) is fertilized with mineral fertilizers with around half of the fertilizer used applied on cereals. Alongside consumption and demand, fertilizer production and application has an impact on the environment. Production of nitrogen based fertilizers is energy intensive, with this traditionally being associated with significant GHG emissions (natural gas is typically used as both an energy vector and a source of hydrogen). Urea emits less carbon dioxide during the production phase than nitrate based products but releases carbon dioxide during the nitrification process. Nitrate based products can have negative environmental impacts beyond the often discussed associated GHG emissions, for example losses of ammonia through volatilization can lead to issues in increasing eco-toxicity. Fertilizer application also has an impact to the environment; more than 90% of EU ammonia emissions come from agriculture, of which 80% comes from manure and 20% from mineral fertilizer (European Commision, 2019). The demand and supply for fertilizers and the environmental impacts associated with it, make this is a suitable product to assess in this worked example as there is much information readily available for reference products.

The following sections include an LCA study for a CO_2 based fertilizer from goal definition to life impact assessment. Further information on interpretation can be found in another worked example included in this series “LCA Interpretation: worked example for CO2 based fertilizer”.

2. Goal definition

1. The goal of this life cycle assessment (LCA) is to compare whether there are quantifiable environmental benefits when using a nitrogen based fertilizer produced from recovered CO_2 (called CO_2 based fertilizer from here on) in place of using fertilizer derived from fossil carbon sources (also known as reference products). The study considers production and application in the UK, in the year 2019.

2. This study is a worked example targeted at a general audience that wishes to understand how to apply the Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization (Zimmermann, et al., 2018) (from now on referred to as only “the guidelines” in this work). The results should not be used in comparative assertions or quoted by third parties.

3. In this worked example the stakeholder wishes to introduce a new bio-fertilizer to the market. This biofertilizer relies on CO_2 captured from anaerobic digestion that reacts with aqueous ammonia and calcium nitrate to produce a fertilizer with 10 % N, 0.6 % P and 0.3 K content. If this biofertilizer is a successful example of a CO_2 utilization technology, then at the very least, carbon emissions shall not be worse than the alternative processes. If carbon emissions are at least neutral, then all other possible environmental impacts also shall be screened.

4. For purposes of this worked example, the final product is classified and treated as a CO_2 based chemical.

3. Scope definition and system boundaries

1. The functional unit is stated as: The fertilizer product needed to produce the same grain yield over 1 ha of winter wheat in the UK (Considering a temperate climate and a PH soil of < 7). Reference flow: 1 kg of fertilizer.

2. Biogas gas is excluded from the scope of the functional unit as it is not our goal to compare energy supply but the fertilizer product instead. However, biogas production is still part of the system as a co-product and allocated as such.

3. The CO_2 based fertilizer will have a different composition and chemical structure than conventional fertilizers, thus in following the guidelines recommendations, the basis for comparison is technical performance and the system boundaries are cradle to grave. There is also the alternative of a preliminary study where the system boundaries can be set at cradle to farm gate.

   In this example the stakeholder has limited information on farming and harvest performance of their CO_2 based fertilizer and has run field tests at a small scale.

   The initial report from field trials states:

   "That the CO_2 based product provides useful yield benefits in a variety of cereal crops; and, as a source of N, the CO_2 based product is comparable to a commercial fertilizer, but may have additional benefits above the provision of N"

   For the purpose of this example, a conservative approach was taken where the CO_2 based product behaved the same as a commercial fertilizer once it was applied to the field. Further tests need to be carried out to confirm the benefits of the product versus a commercial ammonium nitrate fertilizer (used for field trials) and other similar fertilizers. This would indicate that this LCA is best suited as a preliminary study. As part of the worked example both cradle to gate and cradle to grave (with supplementary data) will be assessed to give further insights on how the interpretation of the results varies as you shift boundaries (Refer to LCA Interpretation: worked example for CO2 based fertilizer production). Cradle to grave is still to be considered the main system boundary.

4. The products under assessment are the following:

   - CO_2 based fertilizer (NPK 10 0.6 0.3)
   - Ammonium nitrate from a large fertilizer producer (33.5 N) (CF Fertilizers UK limited, 2019)
   - NPK from a large fertilizer producer (NPK 15 15 15) (Yara, 2019)
   - Ammonium nitrate from Fertilizer Europe (33.5 N) (Fertilizers Europe, 2000)
   - NPK from Fertilizer Europe (NPK 15 15 15) (Fertilizers Europe, 2000)

- Cattle manure (organic fertilizer) from commercial LCI database (Nemecek, 2007)
- Mineral fertilizer from commercial LCI database (Nemecek, 2007)

Note:

There were no commercial fertilizers found that have the same composition as the CO_2 based fertilizer, thus the functional unit refers to grain yield and not to final product quantities. Ammonium nitrate was assessed as it was the stakeholders' choice of fertilizer for field trials, NPK fertilizers were also assessed as the CO_2 based product is labeled as a compound fertilizer. The data obtained for these products is limited to data disclosed to the public. There were no personal communications with the companies behind these products. Cattle manure is also included to study the environmental impact differences between mineral and a commonly used organic fertilizer. For most of these products only the carbon footprint was available, the limitations of this are taken into consideration for the inventory, impact assessment and interpretation stages (Refer to LCA Interpretation: worked example for CO_2 based fertilizer production).

3.1 DEFINING BOUNDARIES

There are three main processes throughout the supply chain of the CO_2 based fertilizer product: anaerobic digestion, biofertilizer production and field production. Each stage has different inputs and outputs and these can vary depending on the specific technologies used for each process. This leads to a wide system with many alternatives as shown in Figure 1 and 2.

As an example, in Figure 1 the anaerobic digestion process can use biomass that has been pre-treated in 4 different ways, the digestate can be processed in 3 different ways for 3 different uses and biogas can either be upgraded to biomethane or for heat in power (CHP) with 5 final destination usage options. Biofertilizer itself can be produced either by chemical, thermal, physical and biological routes.

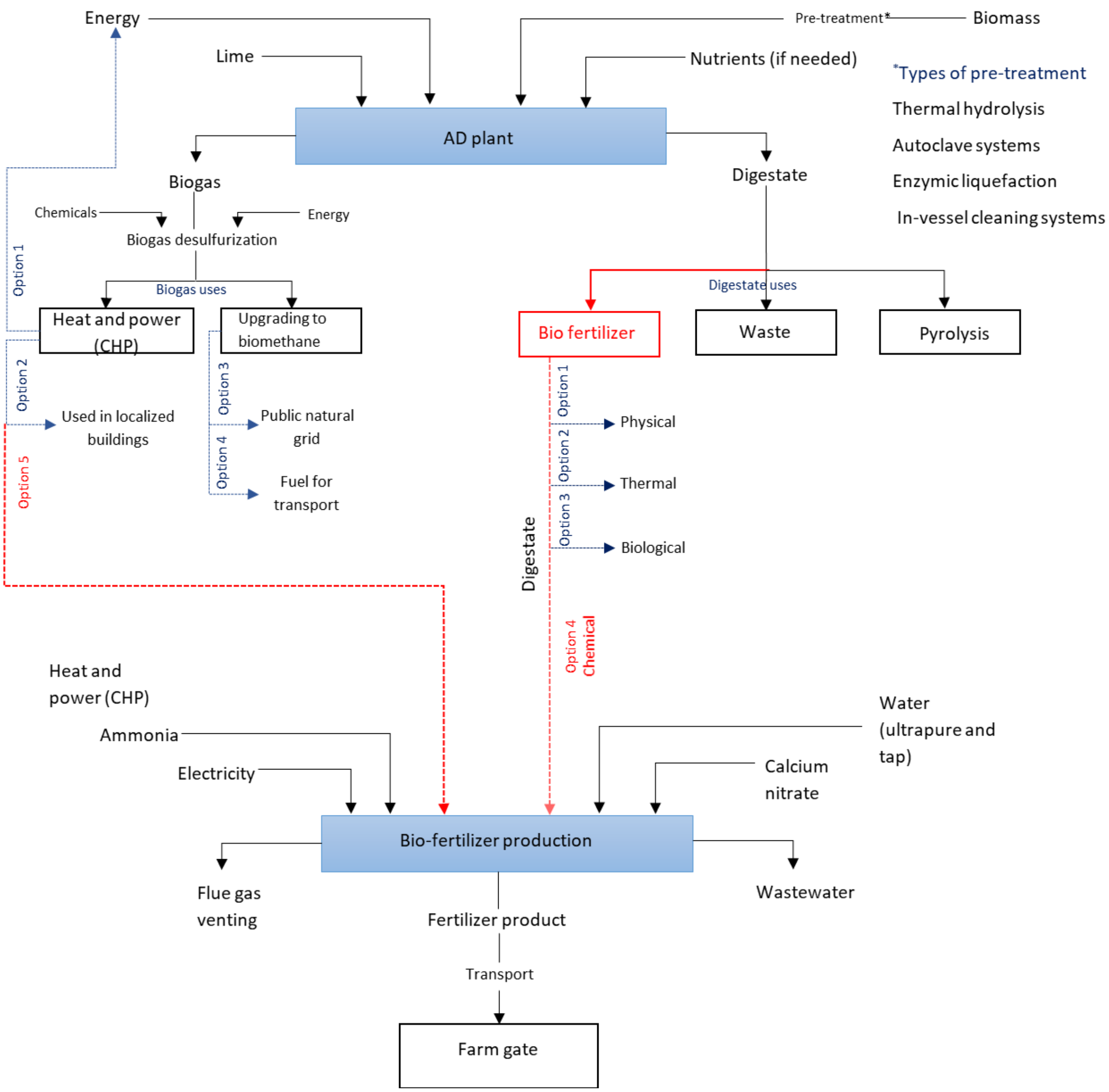
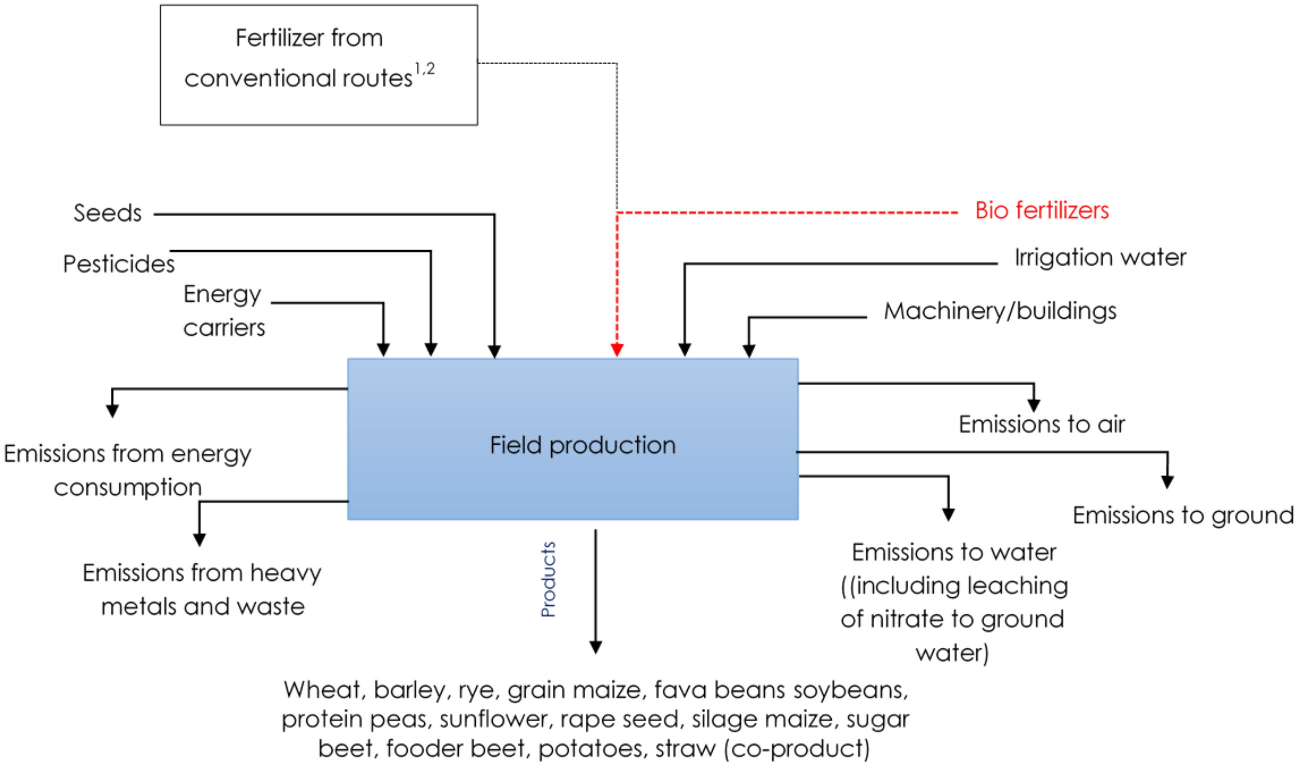


Figure 1 - Process stages for bio-fertilizer production with biomass pre-treatment options, digestate conversion and biogas uses and other process inputs and outputs

Once the biofertilizer is at the farm gate, there is the comparison with other types of fertilizes both mineral and inorganic, the method for fertilizer application, the type of crop and other inputs associated with the fertilizer of choice (**Figure 2**).



[1] Types of fertilizers: Nitrogenous fertilizers, organic nitrogenous fertilizers, phosphate fertilizers, potassic fertilizers, compound fertilizers, complete fertilizers (NPK)

[2] Methods for application of solid fertilizers: Broadcasting, placement, band placement, pellet application

Figure 2 - Inputs and outputs for field production adapted from Ecoinvent "Life Cycle Inventories of agricultural production systems" (Nemecek, 2007)

At the initial assessment stage refining the boundaries can seem overwhelming, what should be assessed and what should not? What if by not assessing a process alternative a significant impact is omitted? Whilst in an ideal assessment all variables and alternatives would be captured within the system boundary, in practice this is often not possible (due to issues such as time constraints, budget limitations, limited personnel, the size of the system keeps expanding, etc.). In this situation it is useful to return to the goal to clarify what is the purpose of the study, modify it if necessary or use it to highpoint where the system boundaries should be. In this example, it was useful to highlight in red (Figure 1 and Figure 2) the two main routes under study:

1. Anaerobic digestion → Digestate/biogas/flue gas for fertilizer production through chemical route → fertilizer application
2. Mineral and organic fertilizer production → Fertilizer application

From this, the boundaries of the system can be simplified (**Figure 3 and 4**) and also include CO_2 sources as suggested in **the guidelines**.

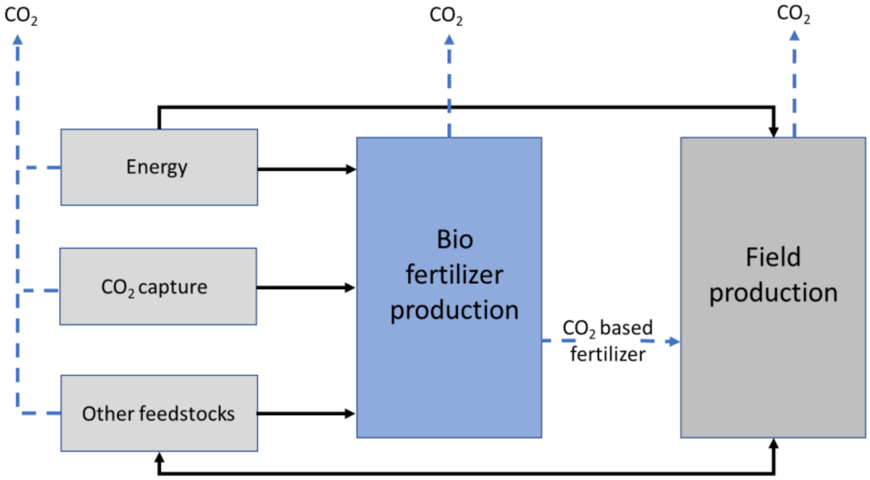


Figure 3 - Simplified boundaries of CO_2 utilization process for CO_2 based fertilizer and application

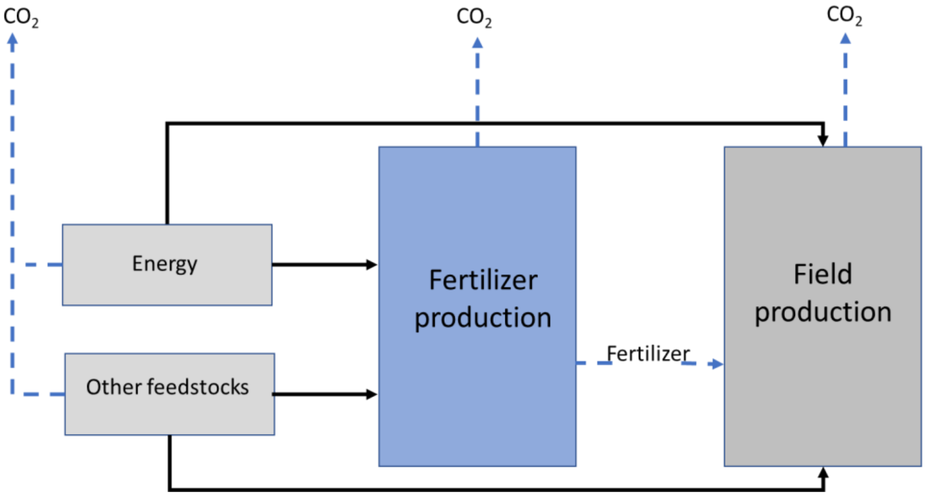


Figure 4 Simplified boundaries of conventional process for fertilizer production and application

Note:

While the other process alternatives do not disappear, they can either be set outside of the boundaries or they can be used as part of a scenario analysis if this is part of the assessment. Whilst all process alternatives might not be of interest to the stakeholder, knowing the environmental impacts of these can be useful for sensitivity analysis that in turn increase the robustness of the study.

3.2 SOLVING MULTIFUNCTIONALITY

In this worked example there are two main products to consider: biogas and biofertilizer. Approximately 93 % of the thermal energy capacity from CHP is used for the mixer-dryer stage in biofertilizer production, therefore biogas is considered to be the co-product and bio-fertilizer the product. No further information was provided by the stakeholder on the use of the remaining thermal energy. It is assumed that it is used in localized buildings and other parts of the plant. However, an alternative scenario is also presented to show the difference between methods for solving cases of multifunctionality.

For the first arrangement (and the one used as the scenario study for assessment), all of the biogas is used within the bio-fertilizer plant and localized buildings. There is no upgrading to biomethane for public grid use or fuel for transport. It is assumed that the anaerobic digester is part of the biofertilizer plant. The comparison between the CO_2 utilization process and the conventional route is as shown in Figure 5, where biogas from anaerobic digestion is an intermediate flow in the biofertilizer plant.

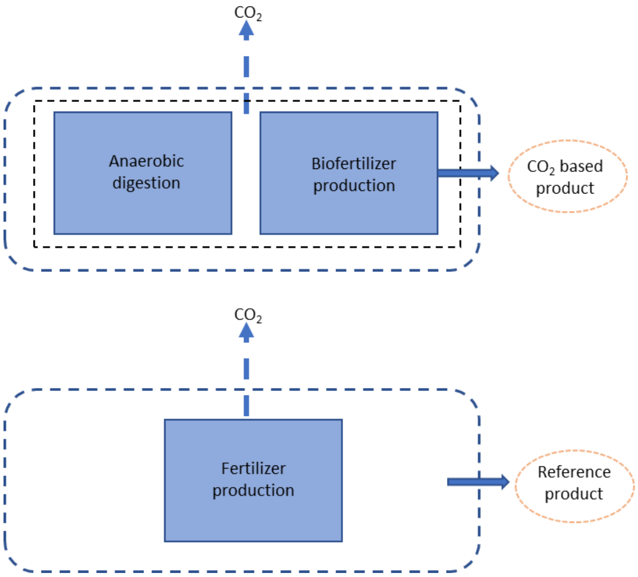


Figure 5 - Scenario where the CO_2 utilization process includes biogas production as an economic flow

In this scenario (Figure 5), no further allocation would be needed if it is assumed that the outputs of the anaerobic digestion were going to be used for biofertilizer production and for no other purpose such as feeding into de public grid since its planning stage. However, this can also lead to questioning whether this is the best use of the energy provided by the AD process. Whilst it is not the aim of this work to discuss how renewable energy should be allocated, if the system was to expand to include biogas as a main product, then the comparison between the CO_2 utilization process and the conventional route would be as shown in Figure 6.

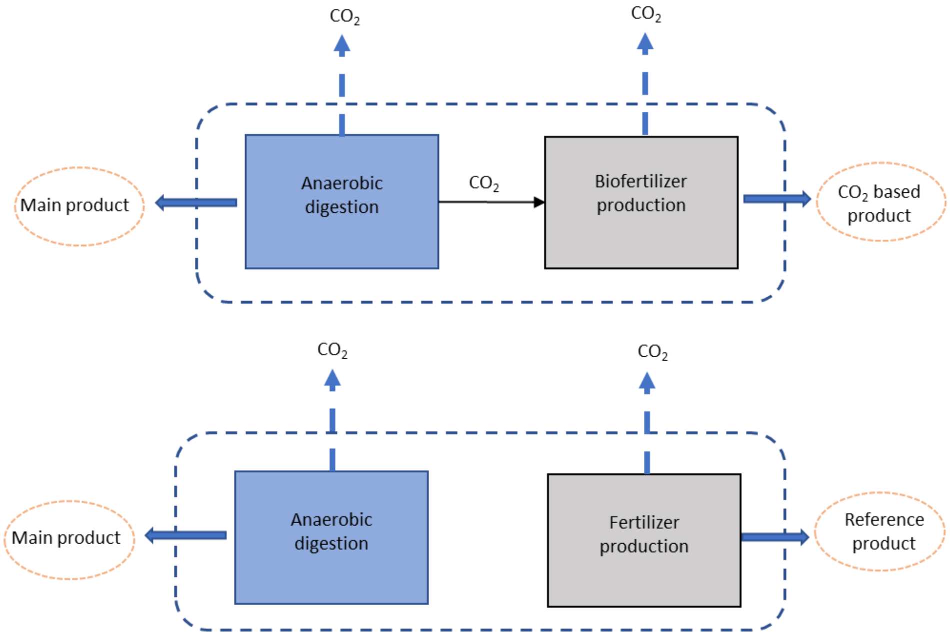


Figure 6 - Scenario where the CO_2 utilization process includes biogas production as an economic flow for biofertilizer production and the excess is used as decentralized energy for the nearby district

Following the hierarchy of methods for solving cases of multi-functionality presented in the guidelines, sub-division cannot solve the multi-functionality problem therefore system expansion is applied. In this second scenario it is assumed that the main product is biogas; and that this is used in a gas engine CHP as a form of decentralized energy for district heating and electricity supply. In this scenario, 93 % of the energy from CHP is still used for biofertilizer production and the 7 % left is used for district heating and electricity supply. In system expansion terms this would mean that the conventional route would also need to provide that 7 % of extra energy for a fair comparison. Or if looked at from a different perspective, the conventional route provides 100 % of the energy from the CHP and the CO_2 utilization process would need additional energy to deliver district heating and electricity supply at the same rate as the conventional route and also run the biofertilizer production simultaneously.

Note:

It is then up to the practitioner to determine whether this expansion is still meaningful for the assessment.

3.3 DATA QUALITY

The CO_2 based fertilizer production data is obtained through a combination of information giving directly by the stakeholder, commercial databases such as Ecoinvent and available literature (journals, NGOs, industry and government reports). For the conventional fertilizer production routes, data was obtained from company websites and supplemented with literature.

As this is a worked example (and not a ISO compliant full study), the inventory used for this work should not be used for comparative studies and further data quality assessment techniques should be applied (e.g. representativeness, completeness, uncertainty, etc.) Table 1 shows basic references on data collected for this example.

Table 1 - Data collected and source used for products under assessment by process stage

Data collected	Source
Anaerobic digestion	
Treatment of biowaste by anaerobic digestion	Ecoinvent database version 3.4
CO_2 based process	Information provided by stakeholder
Fertilizer production	
Ammonium nitrate fertlizers	Company website
NPK fertlizers	Company website
Fertilizers Europe	Online report
CO_2 based process	Information provided by stakeholder
Field production	
Production of wheat, inorganics	Ecoinvent database version 3.4
Production of wheat, organics	Ecoinvent database version 3.4
EMEP/EEA guidebook 2016	Online report
Global database of GHG emission related to feed crops, FAO	Online report

4. Life cycle inventory (LCI)

The inventory includes the flow diagrams of CO_2 based fertilizer production, commercial production of ammonium nitrate, NPK and organic fertilizer. There is also a process description of alternatives under assessment and an input/output table with environmental flows for each process. If there is data that is subject to confidentiality agreements and needs to be excluded from this inventory, this is mentioned throughout the report.

When collecting secondary data for each process stage, the LCA practitioner will come across multiple sources of information that can have many similarities between the processes for which data is being collected. However, often there exists some differences between these processes e.g. location specific, technological or temporal variations on the technology & ultimately the respective inventory. This can lead to the "picking and mixing" of datasets to complete an inventory for a given process. In turn, this can lead to multiple inventories of the same process (as different practitioners may select different elements to "fill in" the missing parts) that may or may not produce a significant difference in the impact assessment (i.e. the sensitivity of individual varying aspects will be a deciding factor on how detrimental "picking and mixing" is).

An example is shown in in Table 2 and Table 3, where Table 2 lists all databases considered (both primary and secondary data) for each of the three main process stages of CO_2 based fertilizer, mineral fertilizers (ammonium nitrate, NPK) and manure production.

Table 2 - List of databases used for this teaching example by process stage

Anaerobic digestion	Fertilizer production	Field production
•Stakeholder data	•Stakeholder data	•Literature-mix data
•Ecoinvent data	•Ecoinvent data, organic fertilizer	•Ecoinvent data, organic fertilizer
	•Ecoinvent data, mineral fertilizer	•Ecoinvent data, mineral fertilizer
	•Commercial Ammonium nitrate	•Fertiliser Europe carbon footprints
	•Commercial NPK	
	•Fertiliser Europe carbon footprints	

Table 3 shows that a total of eighteen life cycle inventories can be created with the collected information. CO_2 based fertilizer alone has six life cycle inventories options where any of these could be used for the final impact assessment. Which of the six options should be used? Would choosing one over the other lead to an erroneous interpretation? Do any of these options truly reflect the process under study after "picking and mixing data"? The guidelines provide us with useful information on how to bridge data gaps with estimation methods. To show the applicability of this methods, all eighteen LCI combinations will be assessed and interpreted to gain understanding on how to build an LCI for CO_2 utilization. For simplification, the LCIs created will be referred from now on as "assessment scenarios" (should not be confused with scenario planning).

Note:

Eighteen life cycle inventories is not the maximum number of inventories available for this process, the number increases as more databases are added. This is only an example to show the sensitivity of LCI data collection.

Table 3 - Assessment scenarios for fertilizer production and land application

	Anaerobic digestion		Fertilizer production		Field production
1 CO_2 based fertilizer					
1a	Stakeholder data	+	Stakeholder data	+	Literature- mix data
1b	Stakeholder data	+	Stakeholder data	+	Ecoinvent dataset, mineral fertilizer
1c	Stakeholder data	+	Stakeholder data	+	Fertilizer Europe carbon footprint
1d	Ecoinvent data	+	Stakeholder data	+	Literature- mix data
1e	Ecoinvent data	+	Stakeholder data	+	Ecoinvent data, mineral fertilizer
1f	Ecoinvent data	+	Stakeholder data	+	Fertilizer Europe carbon footprint
2 Ammonium nitrate					
2a	NA	+	Fertilizer Europe carbon footprint	+	Fertilizer Europe carbon footprint
2b	NA	+	AN carbon footprint	+	Literature- mix data
2c	NA	+	AN carbon footprint	+	Ecoinvent dataset, mineral fertilizer
2d	NA	+	AN carbon footprint	+	Fertilizer Europe carbon footprint
3 NPK					
3a	NA	+	fertilizer Europe carbon footprint	+	FFertilizer Europe carbon footprint
3b	NA	+	NPK carbon footprint	+	Literature- mix data
3c	NA	+	NPK carbon footprint	+	Ecoinvent dataset, mineral fertilizer
3d	NA	+	NPK carbon footprint	+	Fertilizer Europe carbon footprint
4 Organic fertilizer					
4a	NA	+	Literature mix-data	+	Literature- mix data
4b	NA	+	Ecoinvent dataset	+	Ecoinvent dataset, organic fertilizer
5 Fertilizer mix					
5a	NA	+	Ecoinvent dataset	+	Literature- mix data
5b	NA	+	Ecoinvent dataset	+	Ecoinvent dataset, mineral fertilizer

4.1 INVENTORY FOR CO_2 BASED FERTILIZER PRODUCTION

Anaerobic digestate waste is transformed into high-grade compound fertilizer. This process is based on blending three constituents: biomass, ammonia and CO_2. The CO_2 is drawn post-combustion from a bio gas separator and reacted with ammonia and calcium nitrate to produce a solution of ammonium nitrate and calcium carbonate. This solution is mixed with dried solids from the anaerobic digestion plant and the blend goes through a pelletizing plant to make pellets. The product is bagged for storage and or/shipping on lorries. The fertilizer can be spread with a spinner on fields. **Figure 7** shows the flow diagram of this process.

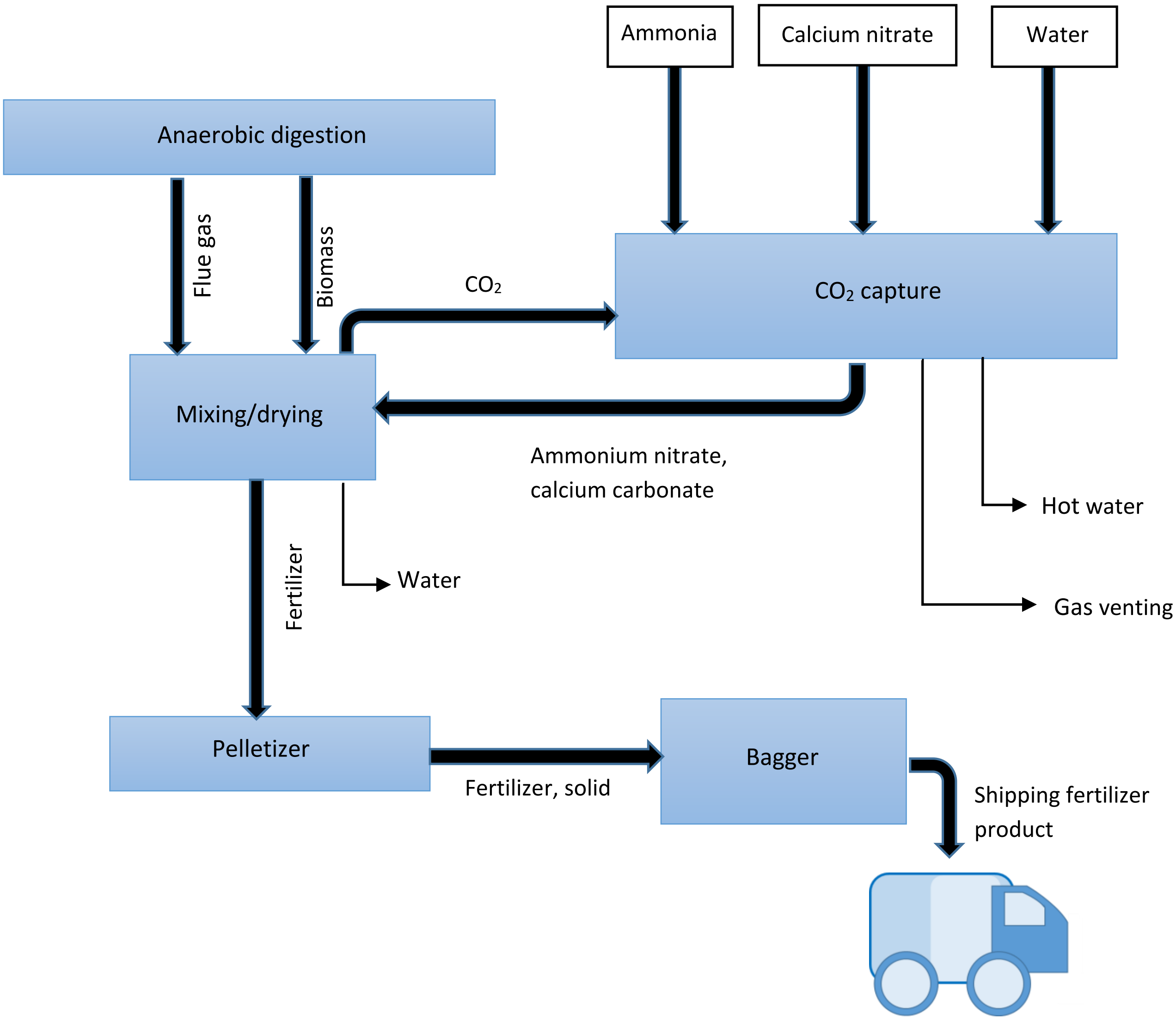


Figure 7 - Flow diagram of CO_2 based fertilizer production (cradle to farm gate)

The information provided by the stakeholder includes: a process flow diagram, mass and energy balance sheet, description of the CO_2 based fertilizer production process, transport distance from gate to farm (return trip) and initial results for field trials of fertilizer use in cereal crops.

Information not given by the stakeholder: inputs to the anaerobic digestion plant, infrastructure data and detailed field emissions of fertilizer use in in cereal crops. Limited information on direct emissions throughout the process and hot water disposal.

Inputs and outputs for anaerobic digestion plant and bio-fertilizer production are shown in Table 4 and 5 scaled to 1 ton of fertilizer produced per day.

Table 4 - Inputs and outputs for anaerobic digestion plant for CO_2 based fertilizer production

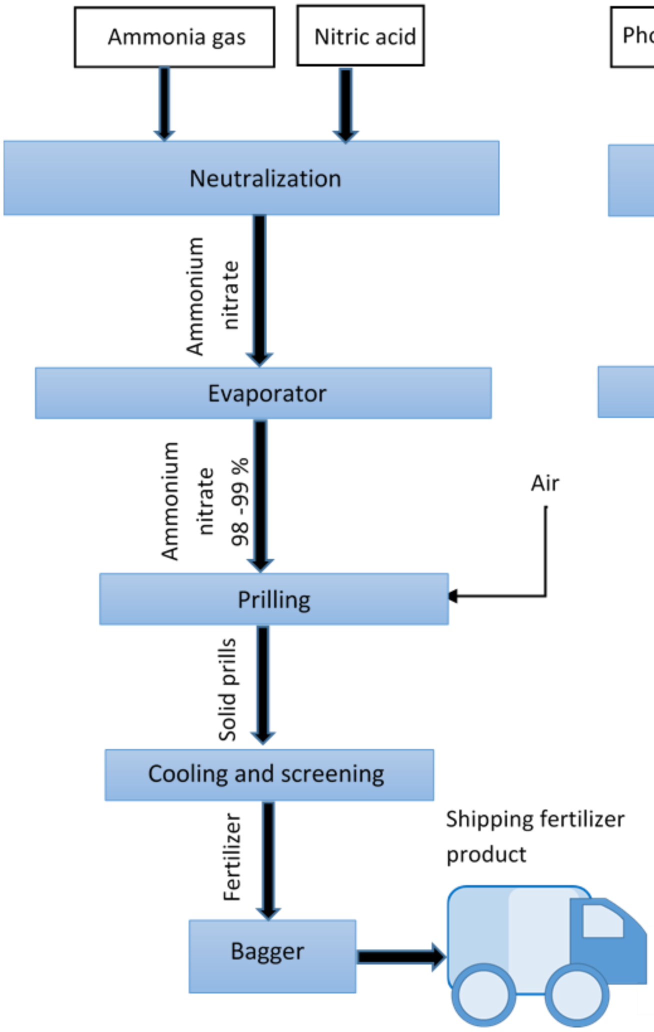
Anaerobic digestion plant: scale 1 ton of fertilizer		
Output	**Quantity**	**Unit**
Digestate	1148	kg
Flue gas	1516	MJ
Thermal energy	0.66	MWh

Table 5 - Inputs and outputs for biofertilizer production process stage for CO_2 based fertilizer

Biofertilizer production: scale 1 ton of fertilizer		
Input	**Quantity**	**Unit**
Digestate	1148	kg
Water	123	kg
Calcium nitrate	redacted	kg
Ammonia	redacted	kg
Thermal energy	0.587	MWh
Electricity	0.194	MWh
Output	**Quantity**	**Unit**
NPK Fertilizer	1000	kg
Flue gas	1476	kg
Biomass water	2114	m^3

4.2 INVENTORY FOR CONVENTIONAL FERTILIZER PRODUCTION

Ammonium nitrate and NPK fertilizers are both assessed as the conventional production routes in this example. CF fertilizers produce Nitram® (CF Fertilizers UK limited, 2019), an ammonium nitrate based fertilizer that has a concentration of 34.5% N. It is a product that has been on the market for 54 years that can be used for both arable crops and grassland. The carbon footprint for Nitram® is 3.4 kg CO_2e per kg Nitrogen at plant gate. A nutrient application rate of 100 N kg/ha is equivalent to 290 kg/ha of product, to improve N efficiency for cereals the company recommends applying no more than 100 kg N/ha in one dressing. Figure 8 shows the process flow diagram of Nitram® production. CF fertilizers also produce compound NPK fertilizers with varying concentrations of N, P, and K. The process flow diagram for all NPK types is shown in Figure 9.



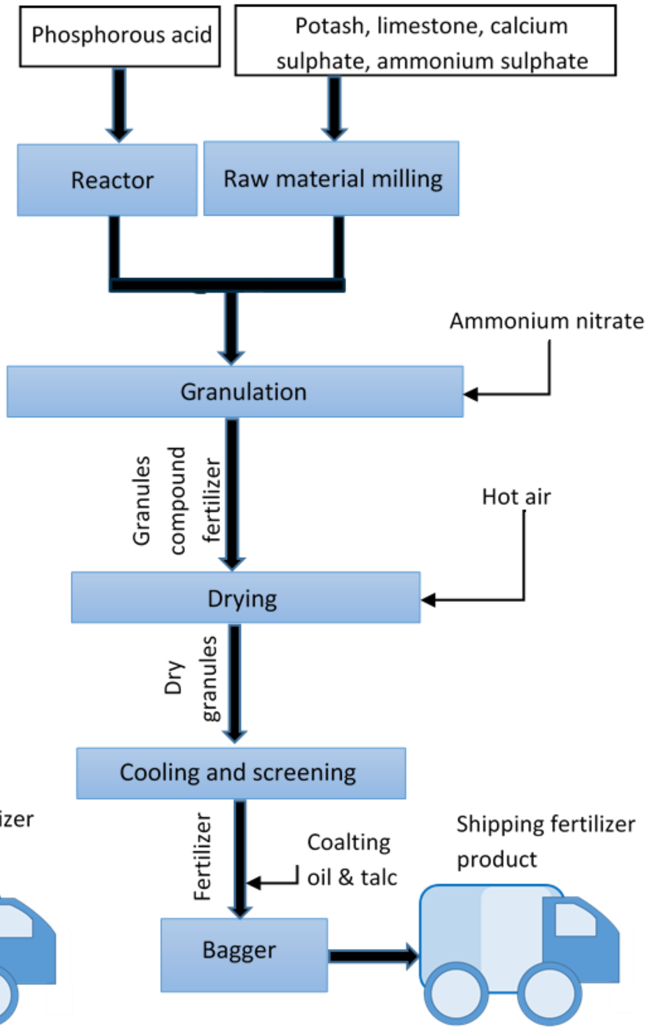


Figure 8 - (left) Process flow diagram for Nitram® fertilizer production

Figure 9 - (right) Process flow diagram for NPK fertilizers production from CF fertilizers

Information gathered on the product: Only information available to the public, this includes a general process flow diagram, product description, carbon footprint, application rates, bag size and recommendations for application to crops. All information available from company website.

Information not specified: mass and energy balance sheets, infrastructure data, detailed emissions information for the production of fertilizer and for the use of it on cereal crops.

Yara (another fertilizer producing company) also offer a 33.5% N fertilizer called YaraBela EXTRAN© and YaraMila© for 15% N 15% P 15% K NPK option (Yara, 2019). Similar to CF fertilizers, the main environmental information given to the public is the carbon footprint. 1.25 kg CO_2e/kg of product (max) for Yarabela EXTRAN© and 0.80 kg CO_2 eq/kg of product for YaraMila©

Note:

Full inventories should be obtained whenever possible. However, it can be difficult to collect detailed information from other companies for comparative studies. This often is the case for CO_2 utilization technologies, where one of the most common research questions is whether a CO_2 utilization based product or service is environmentally beneficial compared to the same product or service derived from fossil carbon sources. In this instance, it is necessary to have both the inventory for the CO_2 utilization process and the fossil carbon source process.

If no other information but the carbon footprint is available for comparison, this should be used as a best case scenario. If the best case scenario does not offer environmental benefits (the carbon footprint for the CO_2 utilization process is larger than the fossil carbon source process). As more information is available, more impact categories can be compared between CO_2 utilization technologies and fossil fuel based processes.

4.3 INVENTORY FOR FIELD PRODUCTION

The stakeholder has carried out cereal field trials for their CO_2 based fertilizer. The trials are of limited scope, but showed that yields were enhanced compared with Nitram® applications on the same day at a similar N level of 6.3 % for winter wheat. The cereal trials were carried out on plots of at least 2 ha. There is no further information available on CO_2 based fertilizer soil application and performance.

Note:

Since there is a lack of information available for field production for the CO_2 utilization process, data is collected from secondary sources. The limitations of using secondary data should be mentioned and secondary data should be replaced with primary as soon as it is available. As mentioned in the scope definition and boundaries, the assessment is suited for cradle to gate as a preliminary study if no field data is available, or for this example as cradle to grave to show the use of multiple inventories for the same process.

Secondary data has been obtained and adapted from CF Fertilizers UK limited (2019), EMEP/EEA (2019), FAO (2017), and Ecoinvent version 3.5. Gabi ts was used to create a process with inputs and outputs shown in Table 6. These inputs were linked to the CO_2 based fertilizer process and to background data from Ecoinvent version 3.4. To calculate emissions factors, the climate is defined as temperate and the PH soil within a normal range of < 7 with operations only occurring once per hectare.

Table 6 - Inputs and outputs for field production of 1 ha of winter wheat

Field production: scale 1 ha of crop (benchmark)		
Input	**Quantity**	**Unit**
Mineral fertilizer	580	kg
Lime	397	kg
Pesticides	2.5	kg (a.i)
Seeds	305	kg
Sowing	26562	Sqm
CO2 binding	12.8	T
Tillage handling	73963	Sqm
Water	3169	m^3
Machinery	14.2	tkm
Output	**Quantity**	**Unit**
Wheat	9.32	t/ha
Emissions to air		
Ammonia	2.8	kg
Nitric Oxide	8	kg
NMVOC	1.09×10^{-8}	kg per kg dm/ha
PM	1.49	kg

4.4 INVENTORIES FROM COMMERCIAL DATABASE

Ecoinvent v 3.4 is used for anaerobic digestion and production of wheat using mineral and organic fertilizer. The anaerobic digestion model used is “Treatment of biowaste by anaerobic digestion”. In this process the mineral content of the biomass is 15 % N, 8 % P_2O_5, 12 % K_2O. The dataset includes the infrastructure for the pre-treatment process, digestion of bio-waste and treatment of the fermented material (de-watering and post composting). The plant has a yearly capacity of 10,000 tonnes with a lifetime of 25 years. The technology is a thermophile, single state digestion with post composting. Energy demand and process emissions of the plant are also included.

The LCI for the production of wheat using mineral fertilizer from Ecoinvent v 3.5 has a cradle to farm gate boundary and includes all machine operations and corresponding machine infrastructure and sheds. Machine operations are soil cultivation, sowing, fertilization, irrigation, weed control, pest and pathogen control, combine-harvest and transport from field to farm. The fertilizer used is a combination of ammonium nitrate, ammonium, sulfate, urea, and ammonia, N, P_2O and K_2O. (There are no further specifications on the type of fertilizer used). The pesticide, herbicide and insecticide composition is not specified; however, it has traces of thiocarbomates, sulfonylureas, acetamide-anillide, organophosphorus and benzoic compounds. It also has glyphosate, triazine and phenoxy compound as herbicides. Direct field emissions are included. This activity ends after harvest and drying of grains at the farm gate.

The Ecoinvent v 3.5 for the production of wheat using organic fertilizer model is also used in this worked example. This model includes average distances and does not provide further manure details. The dataset includes all machine operations and corresponding machine infrastructure and sheds. Machine operations are soil cultivation, sowing, fertilization, irrigation, weed control, pest and pathogen control, combine-harvest and transport from field to farm. Further, direct field emissions are included. This activity ends after harvest and drying of grains at the farm gate. Extra information for organic fertilizer production is obtained from Aguirre Villegas & Larson (2017).

These databases are purchasable and can be used for gate-to-gate inventory estimation with a yield of 95% based on a stoichiometric mass balance as mentioned in the guidelines.

4.5 INVENTORIES FROM PUBLIC AVAILABLE SOURCES

Other inventories considered for this worked example include the carbon footprint information available from Fertilizers Europe (Fertilizers Europe, 2000) and the BAT model for ammonium nitrate production also from Fertilizers Europe. A summary of the carbon footprints used by Fertilizers Europe is shown in Table 7.

Note:

Carbon footprints are not aligned with carbon emissions reported by both CF fertilizers and Yara. Fertilizers Europe report a lower carbon footprint at plant gate than the values reported by fertilizer companies.

However, the last carbon footprint report publicly available by Fertilizers Europe is from 2011 and might not reflect current practices. The LCA practitioner should consider the representativeness of the inventory based on the active years of the dataset. In this worked example, the stakeholder is using the Fertilizers Europe data to compare their own carbon footprint performance and therefore it is included as part of this assessment while also stating the limitations of this comparison.

Table 7 - Carbon footprints of fertilizer product and fertilizer use provided by Fertilizers Europe (2011)

Fertilizer product		Nutrient content	Fertilizer production	Fertilizer use	Fertilizer product + use	
			(At plant gate)	(Soil effects)	Total	Total
			kg CO_2 eq/kg product		kg CO_2 eq/kg product	kg CO_2 eq/kg nutrient
Ammonium nitrate	AN	33.5 % N	1.18	1.89	3.06	9.14
Calcium ammonium nitrate	CAN	27 % N	1	1.38	2.4	8.88
Calcium nitrate	CN	15.5 % N	0.68	0.81	1.5	9.67
Urea	Urea	46 % N	0.91	4.22	5.15	11.19
NPK 15-15-15	NPK	15 % N, 15 % P_2O5, 15 % K_20	0.76	0.85	1.61	10.71

5. Life cycle impact assessment

Impact assessment results are shown throughout this part of the assessment. As mentioned in the guidelines only the results should be presented without interpretation or analysis. The way that results are shown can vary from report to report as there is no definitive way to present them. However, there are many suggestions available from general LCA literature on how to display these in a concise way without omitting results. The methods shown in the technical report by the JRC are used in this section (Zampori L., 2016). The problem-oriented LCA method called "CML method" is also used to express the emissions to the environment through environmental impact categories. This particular method was chosen by following the suggestions in the guidelines.

A note is attached to each set of results presented in this worked example with further comments on how these results are shown in this part of this assessment. Interpretation and analysis can be found in LCA Interpretation: worked example for CO_2 based fertilizer production report.

5.1 CRADLE TO GRAVE IMPACT ASSESSMENT RESULTS

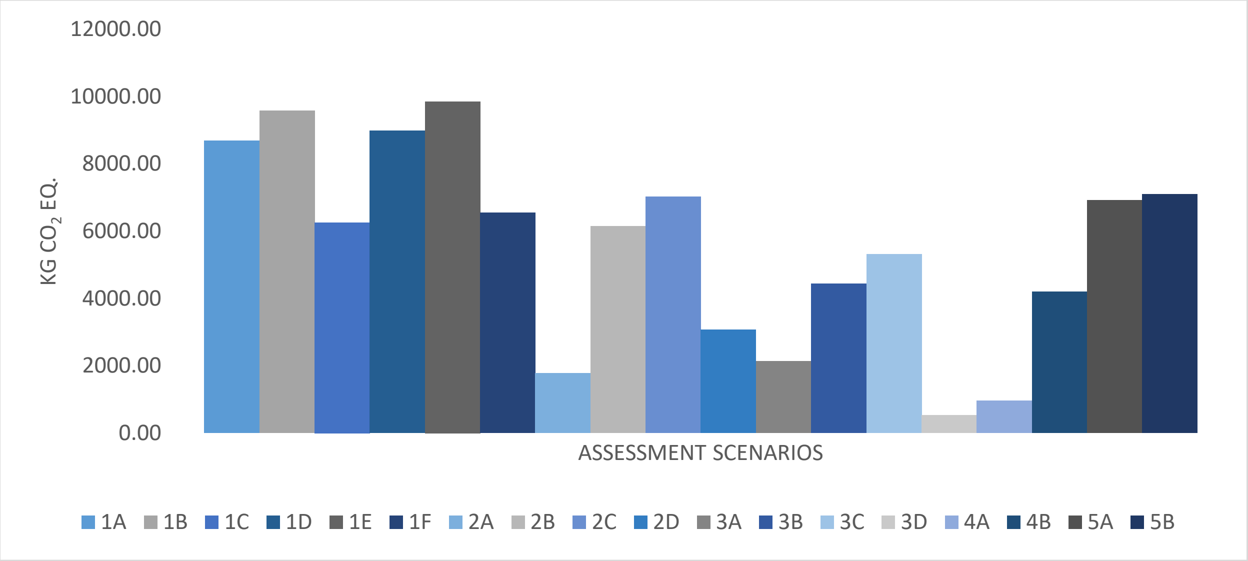


Figure 10 - Climate change impact category results for all eighteen life cycle inventories with cradle to grave boundary assuming the stakeholder's product requires the supply of 200 kg of N to field per hectare of winter wheat crop.

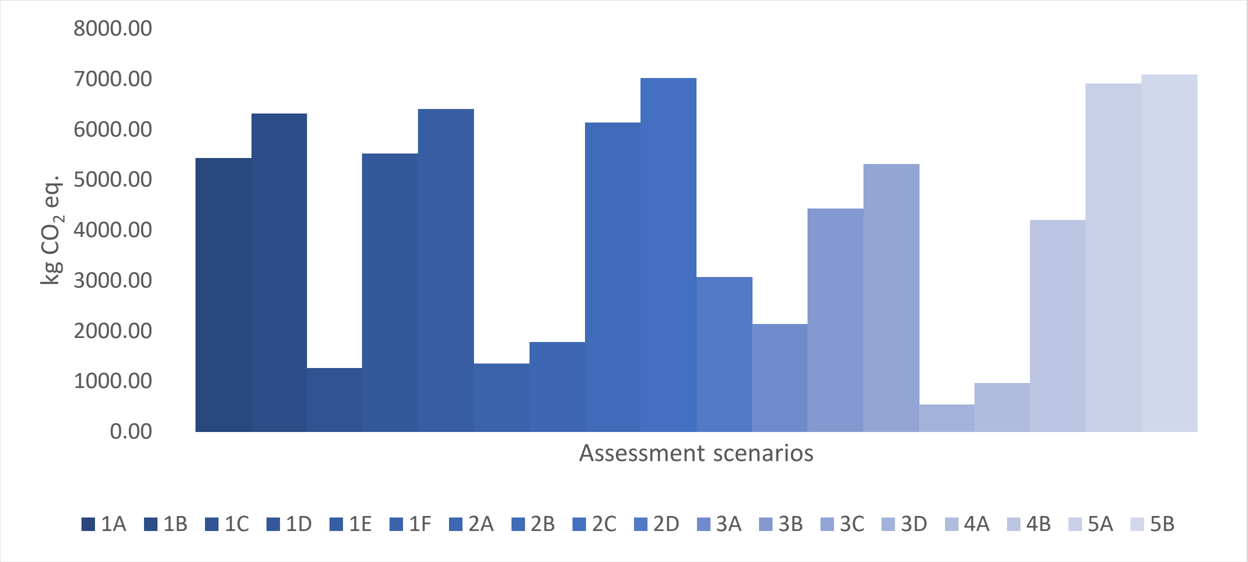


Figure 11 - Climate change impact category results for all eighteen life cycle inventories with cradle to grave boundary assuming the stakeholder's product requires the supply of 580 kg of product to field per hectare of winter wheat crop.

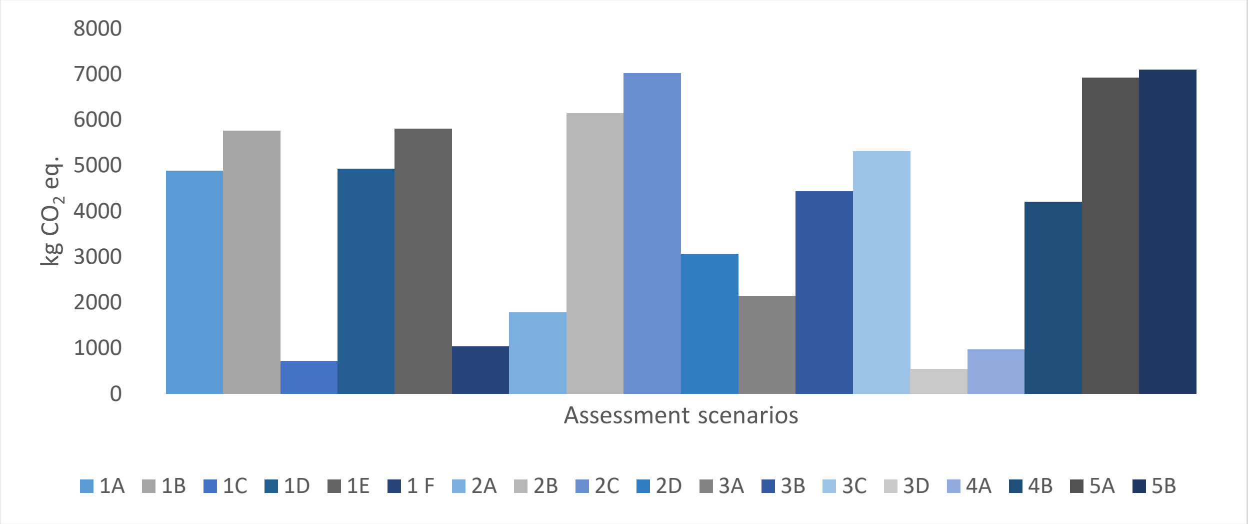


Figure 12 - Climate change impact category results for all eighteen life cycle inventories with cradle to grave boundary assuming the stakeholder's product requires the supply of 325 kg of product to field per hectare of winter wheat crop.

Note:

The graphs only show climate change impact category results as it is the category with sufficient information to compare all inventories across. The goal and scope of the study can be modified if necessary, as conducting an LCA is an iterative process.

5.1.1 CO_2 BASED FERTILIZER PRODUCTION ASSESSMENT SCENARIOS

Note:

A value of zero indicates that there are no direct emissions linked to that stage, if the result is returned as "NA" it assumes that there is not enough information in the LCI to calculate the environmental impact of the chosen impact category.

Table 8 - Relevant life cycle stages for climate change and abiotic depletion impact categories for CO_2 based fertilizer production assessment scenarios. 580 kg of fertilizer per ha of winter wheat crop for ammonium nitrate and CO_2 based fertilizers.

	Life cycle stages	Contribution (%) for each scenario					
		1A	1B	1C	1D	1E	1F
Climate change	Raw material acquisition and pre-processing	23	20	71	24	71	73
	Production of the main product	0	0	0	0	0	0.1
	Product distribution and storage	0.2	0.1	0.5	0.2	0.1	0.5
	Use stage	78	80	28	76	79	27
	End of life	0	0	0	0	0	0
Abiotic depletion	Raw material acquisition and pre-processing	31	24	NA	32	25	NA
	Production of the main product	0	0	NA	0	0	NA
	Product distribution and storage	0.4	0.3	NA	0.4	0.3	NA
	Use stage	69	75	NA	68	75	NA
	End of life	0	0	NA	0	0	NA

Table 9 - Relevant processes for climate change and abiotic depletion impact categories for CO_2 based fertilizer production assessment scenarios. 580 kg of fertilizer per ha of winter wheat crop for ammonium nitrate and CO_2 based fertilizer.

	Most relevant processes	Contribution (%) for each scenario					
		1A	1B	1C	1D	1E	1F
Climate change	Calcium nitrate production	19	16	57	18	16	55
	Ammonia production	4	4	13	4	4	12
	Wheat production	39	36	28	41	36	27
	Treatment of biowaste	0	0	0	2	1	5
	Irrigation to field	25	21	0	25	21	0
	Harvesting	0	6	0	0	6	0
	Wheat seed production	5	4	0	5	4	0
	Other processes	8	13	2	5	13	2
	Total impacts	**100**	**100**	**100**	**100**	**100**	**100**
Abiotic depletion	Calcium nitrate production	18	15	59	18	14	57
	Ammonia production	12	9	37	12	9	36
	Harvesting	0	12	0	0	11	0
	Tillage, harrowing	4	4	0	4	4	0
	Irrigation to field	48	38	0	47	37	0
	Tillage, ploughing	3	2	0	3	2	0
	Wheat seed production	5	4	0	5	4	0
	Other processes	9	17	3	10	18	7
	Total impacts	**100**	**100**	**100**	**100**	**100**	**100**

Note:

The cut-off for accounted impacts was set at 80 % following the methodology of (Zampori L., 2016). This means that all major environmental impact contributions from a process are shown. For most assessment scenarios in this worked example the majority of the impacts fall within 5 processes.

Table 10 - Elementary flows for main processes that contribute to climate change for CO_2 based fertilizer production assessment scenarios. 580 kg of fertilizer per ha of winter wheat crop for ammonium nitrate and CO_2 based fertilizer.

Assessment Scenarios	Process	Contribution (%)to elementary flows				
		Emissions to air	Emissions to fresh water	Emissions to sea water	Emissions to agricultural soil	Emissions to industrial soil
1A	Calcium nitrate production	15	9	39	21	23
	Ammonia production	9	2	7	14	12
	Wheat production	0	0	0	0	0
	Treatment of biowaste	0	0	0	0	0
	Irrigation to field	49	69	21	18	24
	Harvesting	0	0	0	0	0
	Wheat seed production	9	5	14	17	15
	All other processes	18	15	20	30	26
	Total	**100**	**100**	**100**	**100**	**100**
1B	Calcium nitrate production	12	9	31	8	25
	Ammonia production	0	0	0	0	0
	Wheat production	41	9	0	62	0
	Treatment of biowaste	0	0	0	0	0
	Irrigation to field	23	57	13	4	16
	Harvesting	7	5	30	8	18
	Wheat seed production	4	5	9	4	10
	All other processes	14	15	18	14	32
	Total	**100**	**100**	**100**	**100**	**100**
1C	Calcium nitrate production	35	80	80	58	62
	Ammonia production	19	17	14	37	33
	Wheat production	43	0	0	0	0
	Treatment of biowaste	0	0	0	0	0
	Irrigation to field	0	0	0	0	0
	Harvesting	0	0	0	0	0
	Wheat seed production	0	0	0	0	0
	All other processes	3	3	6	4	5
	Total	**100**	**100**	**100**	**100**	**100**
1D	Calcium nitrate production	14	9	37	21	23
	Ammonia production	8	2	6	13	12
	Wheat production	0	0	0	0	0
	Treatment of biowaste	10	0	5	2	1
	Irrigation to field	44	68	20	17	24
	Harvesting	0	0	0	0	0

	Wheat seed production	8	5	13	16	15
	All other processes	16	15	19	30	25
	Total	**100**	**100**	**100**	**100**	**100**
1E	Calcium nitrate production	7	7	24	5	15
	Ammonia production	4	2	4	3	8
	Wheat production	39	9	0	62	0
	Treatment of biowaste	5	0	4	0	0
	Irrigation to field	22	57	13	4	16
	Harvesting	7	5	29	8	18
	Wheat seed production	4	5	8	4	10
	All other processes	14	15	19	14	33
	Total	**100**	**100**	**100**	**100**	**100**
1F	Calcium nitrate production	28	78	72	54	60
	Ammonia production	16	16	12	35	32
	Wheat production	35	0	0	0	0
	Treatment of biowaste	19	3	11	5	0
	Irrigation to field	0	0	0	0	0
	Harvesting	0	0	0	0	0
	Wheat seed production	0	0	0	0	0
	All other processes	2	3	5	5	8
	Total	**100**	**100**	**100**	**100**	**100**

Note: Elementary flows are calculated as the percentage of the total emissions for each assessment scenario. All other processes are those that fall outside the relevant process categories for climate change. Top contributor for each elementary flow and assessment scenario is highlighted in blue.

Table 11 - Impact contributions of environmental quantities for each assessment scenario using the CML method. 580 kg of fertilizer per ha of winter wheat crop for ammonium nitrate and CO_2 based fertilizer.

Environmental quantities	Contribution (%) for each scenario						
	1A	1B	1C	1D	1E	1F	Total
ADP elements	20	24	6	20	24	6	100
ADP fossil	19	24	6	19	25	6	100
AP	13	33	4	14	33	4	100
EP	9	37	3	9	37	3	100
FAETP inf.	16	31	3	16	31	3	100
GWP 100 years	30	27	-5	29	25	-6	100
GWP 100 years, excl biogenic carbon	20	23	6	20	23	7	100
HTP inf.	17	26	5	17	26	9	100
MAETP inf.	21	24	5	21	25	5	100
ODP, steady state	18	24	7	18	25	7	100
POCP	18	27	3	19	28	4	100
TETP inf.	4	45	1	4	45	1	100

Note:

The CML method is used to calculate all environmental impacts as suggested by the guidelines. The LCI for this worked example allows only to show the aggregated results of environmental quantities as there is not enough in depth data for further analysis. The implications of this in the outcome of the study are discussed in the LCA Interpretation: worked example for CO2 based fertilizer production.

5.1.2 AMMONIUM NITRATE (AN), NPK, ORGANIC FERTILIZER PRODUCTION AND FERTILIZER-MIX ASSESSMENT SCENARIOS

Table 12 - Relevant life cycle stages for climate change and abiotic depletion impact categories for ammonium nitrate (AN) fertilizers production assessment scenarios. 580 kg of fertilizer per ha of winter wheat crop.

	Life cycle stages	Contribution (%) for each scenario			
		2A	2B	2C	2D
Climate change	Raw material acquisition and pre-processing	0	0	0	0
	Production of the main product	39	32	28	64
	Product distribution and storage	0	0	0	0
	Use stage	61	68	72	36
	End of life	0	0	0	0
Abiotic depletion	Raw material acquisition and pre-processing	NA	NA	NA	NA
	Production of the main product	NA	NA	NA	NA
	Product distribution and storage	NA	NA	NA	NA
	Use stage	NA	NA	NA	NA
	End of life	NA	NA	NA	NA

Table 13 - Relevant life cycle stages for climate change and abiotic depletion impact categories for NPK fertilizers production assessment scenarios. 325 kg of fertilizer per ha of winter wheat crop.

	Life cycle stages	Contribution (%) for each scenario			
		3A	3B	3C	3D
Climate change	Raw material acquisition and pre-processing	0	0	0	0
	Production of the main product	32	6	5	48
	Product distribution and storage	0	0	0	0
	Use stage	68	94	95	52
	End of life	0	0	0	0
Fossil depletion	Raw material acquisition and pre-processing	NA	NA	NA	NA
	Production of the main product	NA	NA	NA	NA
	Product distribution and storage	NA	NA	NA	NA
	Use stage	NA	NA	NA	NA
	End of life	NA	NA	NA	NA

Table 14 - Relevant life cycle stages for climate change and abiotic depletion impact categories for organic and mineral fertilizer production assessment scenarios for the production 1 ha of winter wheat crop.

	Life cycle stages	Contribution (%) for each scenario			
		4A	4B	5A	5B
Climate change	Raw material acquisition and pre-processing	0	0	0	0
	Production of the main product	15	0	28	0
	Product distribution and storage	0	0	0	0
	Use stage	85	100	72	100
	End of life	0	0	0	0
Fossil depletion	Raw material acquisition and pre-processing	NA	0	0	0
	Production of the main product	NA	0	32	0
	Product distribution and storage	NA	0	0	0
	Use stage	NA	100	68	100
	End of life	NA	0	0	0

Note:

A different rate of fertilizer is applied to the field depending on the type of fertilizer. To be able to compare between scenarios functionality has to be the same, thus using the crop yield as the functional unit in all cradle to grave assessment scenarios.

There are no further results shown for these assessment scenarios as commercial databases are aggregated. The benefit and drawbacks of having aggregated results are discussed in LCA Interpretation: worked example for CO2 based fertilizer production.

5.2 CRADLE TO GATE IMPACT ASSESSMENT RESULTS

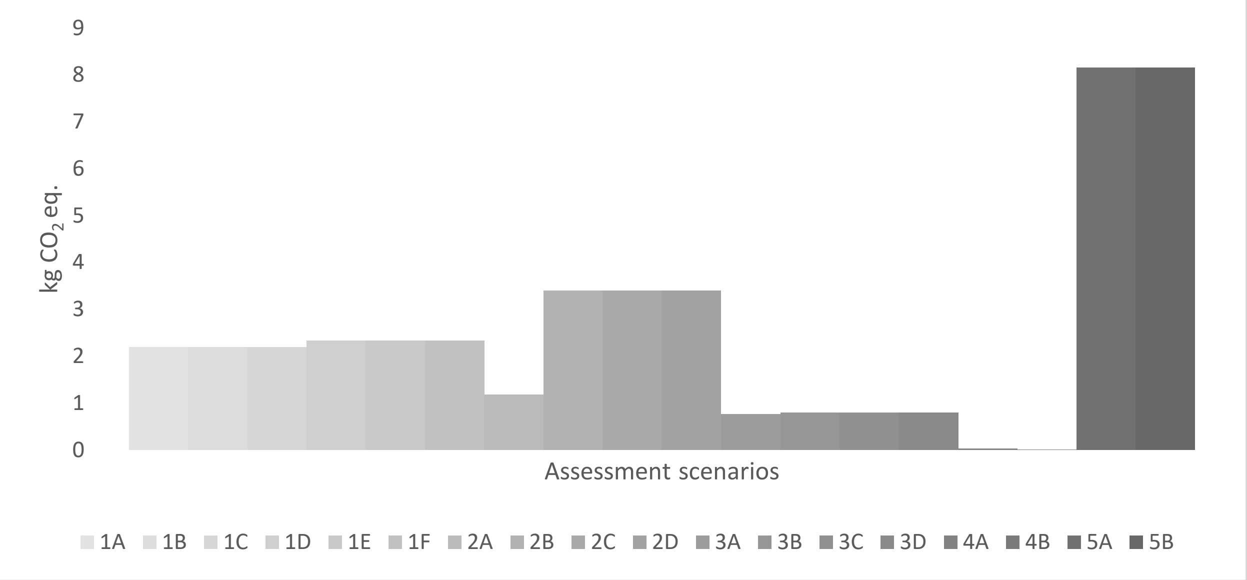


Figure 13 - Climate change impact category results for all eighteen life cycle inventories with cradle to farm gate boundary with a reference flow of 1 kg of fertilizer.

Note:

As with cradle to grave, only climate change impact category results can be shown across all eighteen inventories. Data for other environmental quantities is either not publicly available, inconsistent or incomplete. LCA Interpretation: worked example for CO2 based fertilizer production analyses this further.

5.2.1 CO$_2$ BASED FERTILIZER PRODUCTION ASSESSMENT SCENARIOS-CRADLE TO GATE

Table 15 - Relevant life cycle stages for climate change and abiotic depletion impact categories for CO$_2$ based fertilizer production assessment scenarios per reference flow of 1 kg of fertilizer. produced.

	Life cycle stages	Contribution (%) for each scenario					
		1A	1B	1C	1D	1E	1F
Climate change	Raw material acquisition and pre-processing	99.2	99.2	99.2	99.2	99.2	99.2
	Production of the main product	0.2	0.2	0.2	0.2	0.2	0.2
	Product distribution and storage	0.7	0.7	0.7	0.6	0.6	0.6
	Use stage	0	0	0	0	0	0
	End of life	0	0	0	0.01	0.01	0.01
Abiotic depletion	Raw material acquisition and pre-processing	99	99	99	99	99	99
	Production of the main product	0	0	0	0	0	0
	Product distribution and storage	1	1	1	1	1	1
	Use stage	0	0	0	0	0	0
	End of life	0	0	0	0	0	0

Table 16 - Relevant processes for climate change and abiotic depletion impact categories for CO$_2$ based fertilizer production assessment scenarios per reference flow of 1 kg of fertilizer produced.

	Most relevant processes	Contribution (%) for each scenario					
		1A	1B	1C	1D	1E	1F
Climate change	Calcium nitrate production	18	18	18	75	75	75
	Ammonia production	80	80	80	17	17	17
	Transport to farm gate	1	1	1	1	1	1
	Treatment of biowaste	0	0	0	6	6	6
	Other processes	2	2	2	2	2	2
	Total impacts	**100**	**100**	**100**	**100**	**100**	**100**
Abiotic depletion	Calcium nitrate production	59	59	59	57	57	57
	Ammonia production	37	37	37	36	36	36
	Transport to farm gate	1	1	1	1	1	1
	Treatment of biowaste	0	0	0	4	4	4
	Total impacts	2	2	2	2	2	2
	Total impacts	**100**	**100**	**100**	**100**	**100**	**100**

Table 17 - Elementary flows for main processes that contribute to climate change for CO_2 based fertilizer production assessment scenarios for a reference flow of 1 kg of fertilizer produced.

Assessment Scenarios	Process	Contribution (%)to elementary flows				
		Emissions to air	Emissions to fresh water	Emissions to sea water	Emissions to agricultural soil	Emissions to industrial soil
1A, 1B, 1C	Calcium nitrate production	61	80	80	58	62
	Ammonia production	34	17	14	37	33
	Treatment of biowaste	0	0	0	0	0
	Transport to farm gate	1	1	1	3	3
	All other processes	4	3	6	2	3
	Total	**100**	**100**	**100**	**100**	**100**
1D,1E,1F	Calcium nitrate production	43	78	72	54	60
	Ammonia production	24	16	12	35	32
	Treatment of biowaste	30	3	11	5	0
	Irrigation to field	1	1	0	2	2
	Total	**100**	**100**	**100**	**100**	**100**

Table 18 - Impact contributions of environmental quantities for each assessment scenario using the CML method for a reference flow of 1 kg of fertilizer produced.

Environmental quantities	Contribution (%) for each scenario						
	1A	**1B**	**1C**	**1D**	**1E**	**1 F**	**Total (%)**
ADP elements	17	17	17	17	17	17	100
ADP fossil	16	16	16	17	17	17	100
AP	16	16	16	17	17	17	100
EP	17	17	17	17	17	17	100
FAETP inf.	16	16	16	17	17	17	100
GWP 100 years	15	15	15	18	18	18	100
GWP 100 years, excl biogenic carbon	16	16	16	17	17	17	100
HTP inf.	17	17	17	17	17	17	100
MAETP inf.	16	16	16	17	17	17	100
ODP, steady state	17	17	17	17	17	17	100
POCP	14	14	14	19	19	19	100
TETP inf.	17	17	17	17	17	17	100

Note:

The method used in Section 4.1.2 to obtain results and display them, is also used for the cradle to gate assessment. Use stage is not accounted for and the most relevant processes change with a smaller boundary. All inputs and outputs are scaled down to produce and transport 1 kg of fertilizer to the farm gate.

5.2.2 AMMONIUM NITRATE (AN), NPK, ORGANIC FERTILIZER PRODUCTION AND FERTILIZER-MIX ASSESSMENT SCENARIOS

If the LCI inventories for other reference processes presented in this work are used as shown, then there is little un-aggregated information available to show contributions to life cycle stages, processes and reference flow. At this point, the scope and the goal of the study should be revised and adjusted as necessary. This could lead to further research to expand the current inventories. Alternatively, if aggregated results are sufficient without the need for hot-spot analysis of reference technologies then there is no need for changes in the goal and scope. Further discussion in LCA Interpretation: worked example for CO_2 based fertilizer production.

6. Conclusions

This worked example shows the applicability of the “the guidelines” to a CO_2 utilization technology with a focus on life cycle inventory and life cycle impact assessment phases. The product under assessment is a CO_2 based fertilizer that uses recovered carbon dioxide from industrial power generators. The goal of the LCA study is to compare whether there are reductions in environmental impact when using the CO_2 based fertilizer compared to fertilizer produced from fossil carbon sources. The boundaries of the study are cradle to grave with a second example of cradle to farm gate boundaries for preliminary studies. The functional unit is stated as: The fertilizer product needed to produce the same grain yield over 1 ha of winter wheat in the UK (Considering a temperate climate and a pH soil of < 7) with a reference flow of 1 kg.

A specific aim of this work was to document the results of “picking and mixing” data for the life cycle inventory phase. Results from this worked example showed that “picking and mixing data” leads to multiple inventories of the same process. In this case, eighteen different inventories (refer to as “assessment scenarios” in the study) were created from five types of fertilizer product: CO_2 based, ammonium nitrate, NPK, organic and mineral fertilizer. Data was collected from commercial LCI databases, from the stakeholder, company websites for reference products and a mix of literature sources. This illustrated the many possible options in which the LCA practitioner can arrive at different results in the impact assessment phase and how this will be reflected in the interpretation (refer to “LCA Interpretation: worked example for CO_2 based fertilizer” for more information on the interpretation phase). The stakeholders mainly provided gate to gate data as field trials are in early stages, for the reference products only the carbon footprint is disclosed to the public directly from the fertilizer companies, the LCIs from commercial databases have full inventories but have generic/and or different processes to the CO_2 based and reference product, and lastly, data from literature is mixed from different products/processes/studies. This created an ideal setup for “picking and mixing” data that is often seen in LCAs for CO_2 utilization technologies as there are few (if any) full inventories with environmental data for both the product under study and the reference product.

As mentioned above, this resulted in the production of eighteen assessment scenarios each with their own life cycle impact assessment for both cradle to grave and cradle to gate boundaries. For CO_2 based fertilizer product there are six assessment scenarios with three different field application rates. For ammonium nitrate and NPK fertilizers there are four assessment scenarios for each and two assessment scenarios for both organic and mineral fertilizers. The life cycle impact assessment is split into life cycle stages, relevant process stages, elementary flows and environmental quantities following the methods shown in a guide to interpret life cycle results published by the JRC. The LCIA results are dependent on the inventory, thus not all eighteen assessment scenarios will have the same split of stages/processes/elementary flows or environmental quantities.

All results from the LCIA phase are used for the second worked example “LCA Interpretation: worked example for CO_2 based fertilizer”.

7. References

Aguirre Villegas, H., & Larson, R. (2017). Evaluating greenhouse gas emissions from dairy manure management practices using survey data and lifecycle tools. *Journal of Cleaner Production, 143*, 169-179.

CF Fertilizers UK limited. (2019). *CF Fertilizers*. Retrieved September 12, 2019, from https://www.cffertilisers.co.uk/fertiliser-products/nitrogen/nitram/

EMEP/EEA. (2019). EMEP/EEA air pollutant emission inventory guidebook 2019. Luxembourg: European Environment Agency. Retrieved from https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

European Commision. (2019). *Fertiliser in the EU Prices, trade and use.* Brusseles. Retrieved from https://ec.europa.eu/info/sites/info/files/food-farming-fisheries/farming/documents/market-brief-fertilisers_june2019_en.pdf

FAO. (2017). *Global database of GHG emissions related to feed crops.* Rome: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/3/a-i8275e.pdf

FAO. (2017). *World fertilizer trends and outlook to 2020.* Rome: Food and Agriculture Organization of the United Nations. Retrieved from http://www.fao.org/3/a-i6895e.pdf

Fertilizers Europe. (2000). Best available techniques for pollution prevention and control in the European fertlizer industry. Brussels: Fertilizers europe. Retrieved from https://www.fertilizerseurope.com/wp-content/uploads/2019/08/Booklet_1_final.pdf

Nemecek, T. K. (2007). Life cycle inventories of agricultural production systems. Zurich and Dubendorf: Ecoinvent. Retrieved from https://db.ecoinvent.org/reports/15_Agriculture.pdf

Yara. (2019). *Yara*. Retrieved August 15 , 2019, from https://www.yara.com/crop-nutrition/products-and-solutions/global-fertilizer-brands/

Zampori L., S. E. (2016). *Guide for interpreting life cycle assessment result.* Brussels: European Comission. Retrieved from https://publications.jrc.ec.europa.eu/repository/bitstream/JRC104415/lb-na-28266-en-n.pdf

Zimmermann, A., Wunderlich, J., Buchner, G., Müller, L., Armstrong, K., Michailos, S., . . . Williams, E. (2018). *Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO2 Utilization.* doi:10.3998/2027.42/145436