

Global GHG abatement potential for the
nitrogen fertilizer industry up to 2030

Global GHG abatement potential for the nitrogen fertilizer industry up to 2030

Marta Rangel Campos
Studentnr 3101649
martarangelcampos@gmail.com

Energy Science Master
Supervision by Prof. Dr. Ernst Worrell
ECTS 35
November 2011

Acknowledgments

I would like to thank to Professor Ernst Worrell for his coordination and support during this research. I also want to thank Deger Saygin, PhD researcher, for his assistance on providing me relevant data for this survey and to Aikaterini Kermeli, junior researcher, for the numerous talks we had. At last, I want to thank my family and friends for all the support in this period of my life

Summary

This dissertation studies the global GHG abatement potential of nitrogen fertilizer industry up to 2030. In order to acknowledge it, a data base of the major nitrogen producing countries that make up 80% of global production was created. The data base focused on energy use, energy intensities, GHG emissions and intensities of the three major fertilizers: ammonia, urea and nitric acid. Moreover the current technology status, the technological options to increase energy efficiency and reduce GHG emissions, the costs of it and the rate of implementation was discussed and analysed. Besides the baseline scenario on 2005 two other scenarios were defined to contrast and compare the forthcoming situation up to 2030: frozen efficiency scenario and business as usual scenario. It was assumed that on the frozen efficiency scenario the technological development remains constant as in 2005 and on the business as usual scenario the new production is assumed to run on BAT levels the old production increases its efficiency by a certain percentage per year.

The results show that ammonia is the biggest nitrogen fertilizer. According to the model, its production is expected to increase 30% from 2005 (126Mt) to 2030 (179Mt). China is the biggest contributor (42%) followed, in a much lesser degree, by India (13%), Indonesia (7%), Russia and US (6%). The global GHG emissions released in 2005 due to nitrogen fertilizers reached 418 Mt CO₂. The total GHG emissions are expected to increase 26% from 2005 to 2030 in the frozen efficiency scenario (564 Mt CO₂ in FE), and 14% in the business as usual scenario (486 Mt CO₂ in BAU). The global CO₂ abatement potential represent a 27,4% decrease in the frozen efficiency scenario and 24,4% in the business as usual scenario.

Table of contents

Acknowledgments.....	3
Summary	4
Table of contents.....	5
List of tables.....	7
List of figures.....	8
List of abbreviations	9
1 Introduction	10
Research objective	12
2 Nitrogen fertilizer industry.....	13
2.1 Historical trends of nitrogen fertilizer consumption.....	13
2.2 Ammonia’s relevance and characterization	15
3 Outline of the processes	17
3.1 Ammonia process	17
3.2 Urea process.....	20
3.3 Nitric Acid process	21
4 Nitrogen production process: energy consumption and GHG emissions.....	22
4.1 Ammonia production process: energy consumption and CO ₂ emissions	22
4.2 Urea production process: energy consumption and CO ₂ emissions.....	23
4.3 Nitric Acid production process: energy consumption and N ₂ O emissions.....	24
5 Methodology.....	26
5.1 The model	26
5.2 Cost supply curves	26
5.3 System boundaries.....	27
6 Technology measures	31
6.1 Ammonia’s technology measures	31
6.2 Urea’s technology measures	33
6.3 Nitric acid’s technology measures.....	33
7 Technology assumptions.....	35
7.1 Nitrogen production data.....	35
7.2 Specific energy consumption data.....	35
7.3 Fuel mix.....	36
7.4 Fuel prices	37
7.5 Investment costs difference	37

7.6	Capital stock turnover	38
8	Baseline scenarios	39
8.1	Baseline nitrogen production	39
8.2	Baseline energy consumption	40
8.3	Baseline CO ₂ emissions	41
9	Results.....	43
9.1	Energy consumption according to the baseline scenarios	43
9.2	GHG emissions according to baseline scenarios.....	43
9.3	Energy and emissions savings potentials in the baseline scenarios	44
9.4	Using a different methodology	47
9.5	The influence of retrofit measures and cost-effective retrofit measures on total energy consumption and GHG emissions for both scenarios	48
9.6	Specific energy consumption of ammonia per country according to the different scenarios.....	49
9.7	Specific energy consumption of urea per country according to the different scenarios	51
9.8	Emission reduction of the top four nitrogen fertilizers countries and The Netherlands	53
10	Sensitivity analysis	56
10.1	Influence of discount rate	56
10.2	Influence of energy prices	57
11	Discussion.....	59
11.1	Nitrogen fertilizers: production and production growth rate.....	59
11.2	Fuel mix, specific energy consumption and fuel prices	59
11.3	Methodology and technological options	60
11.4	Comparison with other studies: energy and GHG emissions abatement potential	61
12	Conclusion	62
13	References.....	63

List of tables

Table 1.1: Overview of the raw materials and the major issues concerning nitrogen fertilizers...	12
Table 2.1: Global N ₂ O emissions (Ramirez et al 2003).....	14
Table 2.2: Applied processes and feedstock of ammonia's production.....	15
Table 4.1: Energy use in the Chemical and Petrochemical Industry 2004 (Excluding Electricity)(IEA 2008).	22
Table 4.2: Data collection of the theoretical minimum and Best Available Technology of SEC of ammonia production.....	23
Table 4.3: Data collection presented by Rafiqul 2005.....	23
Table 5.1: List of technologies proposed in this research.....	28
Table 5.2: Nitrogen production and share of production in terms of total production in 2005....	29
Table 6.1: Technology proposed by Bartels et al (2008).....	31
Table 6.2: Technologies proposed by Rafiqul et al (2003).	32
Table 6.3: Technologies proposed by (ICARUS-4 Nieuwlaar 2001)	32
Table 6.4: Technology measure of urea.....	33
Table 6.5: Technology measure of nitric acid.....	34
Table 7.1: SEC of ammonia and urea per country.	36
Table 7.2: Fuel prices (2005).	37
Table 7.3: Table from IEA report Gielen 2003. Table 7.4: Adapted table for end use in this research.	38
Table 8.1: Differences between Frozen efficiency and Business as usual scenarios.	40
Table 9.1: Average costs of technologies and energy savings potential of ammonia fertilizer.....	45
Table 9.2: Average costs of technologies and GHG emissions savings potential of ammonia fertilizer.....	46
Table 9.3: Average cost of urea technology, energy savings and CO ₂ potential of urea fertilizer. .	46
Table 9.4: Average cost of nitric acid technology and the correspondent CO ₂ savings.....	47
Table 9.5: Specific energy consumption of ammonia per country according to the different scenarios.....	50
Table 9.6: Specific energy consumption of urea for China, India and The Netherlands according to the different scenarios.	52
Table 10.1: Results of sensitivity analysis on discount rates for ammonia urea.....	56
Table 10.2: Sensitivity analysis results of urea.....	57
Table 10.3: Results of sensitivity analysis on fuel prices for ammonia and urea.....	57
Table 11.1: Fuel mix share differences.	59
Table 11.2: Comparison with SERPEC study.....	60

List of figures

Figure 1.1: Projected development of cereal production, global population, fertilizer use and arable land (FAO 2003).	10
Figure 1.2: Fertilizer production routes (EFMAa, 2000).	11
Figure 1.3: Main countries producing ammonia fertilizer in 2007 (USGS 2009).	11
Figure 2.1: Fertilizer consumption per nutrient (Yara 2008).	13
Figure 2.2: Ammonia and urea production (Yara 2008).	13
Figure 2.3: Evolution of the atmospheric N ₂ O concentration (Ramirez et al 2003).	14
Figure 2.4: Global ammonia capacity by feedstock 2007 (IFA 2008).	16
Figure 3.1: Steam reforming natural gas (EFMA BAT No. 1 1995).	17
Figure 3.2: Heavy fuel oil (non catalytic) gasification process (Pollution Control in Fertilizer Production 1994).	17
Figure 3.3: Pulverized coal (non catalytic) gasification process (Pollution Control in Fertilizer Production 1994).	18
Figure 3.4: Light hydrocarbon catalytic partial oxidation process (autothermal reforming) (EFMA BAT No. 1 1995).	18
Figure 3.5: Diagrams are presented in UNEP 2000.	18
Figure 4.1: Net export of Nitric Acid plants (GJ/t HNO ₃ -N) (Kongshaug 1998; Wisenberger 2001)	24
Figure 8.1: Ammonia production in 2005 and 2030.	40
Figure 8.2: GHG emissions due to ammonia, urea and nitric acid processes in the 2005 baseline scenario.	41
Figure 9.1: Energy consumption according to the baseline scenarios.	43
Figure 9.2: GHG emissions according to the baseline scenarios.	44
Figure 9.3: Overall energy savings potential of ammonia production for the frozen efficiency and business as usual scenarios.	45
Figure 9.4: Overall CO ₂ emissions savings of ammonia production for the frozen efficiency and business as usual scenarios.	46
Figure 9.5: Costs of technologies and cumulative energy savings potential of ammonia fertilizer for the frozen efficiency scenario using a 30% discount rate.	47
Figure 9.6: Impact of retrofit measures and cost-effective retrofit measures in both scenarios in terms of energy consumption.	48
Figure 9.7: Impact of retrofit measures and cost-effective retrofit measures in both scenarios in terms of GHG emissions.	49
Figure 9.8: Specific energy consumption of ammonia for China, India and The Netherlands according to the different scenarios.	51
Figure 9.9: Specific energy consumption of urea for China, India, Indonesia, United States and The Netherlands according to the different scenarios.	53
Figure 9.10: Emission reduction of the top 4 nitrogen fertilizers countries and The Netherlands.	54
Figure 10.1: Ammonia's cost supply curve (FE scenario).	56
Figure 10.2: Ammonia's cost supply curve (BAU scenario).	56
Figure 10.3: Urea's cost supply curve (FE and BAU scenario).	57
Figure 10.4: Urea's cost abatement curve (FE and BAU scenario).	57

List of abbreviations

IEA	International Energy Agency
US-EPA	US Environmental Protection Agency
IFA	International Fertilizer Industry
IFDC	International Fertilizer Development Centre
FAO	Food and Agriculture Organization
UNFCCC	United Nations Framework Convention on Climate Change
GHG	Greenhouse Gas
GWP	Global Warming Potential
SEC	Specific Energy Consumption
BPT	Best Practice Technology
BAT	Best Available Technique
EFMA	European Fertilizer Manufacturers Association
BREF	Best Available Technique Reference Document
IPCC	Intergovernmental Panel on Climate Change
UNEP	United Nation Environment Programme
CSC	Cost Supply Curve
CCE	Cost of Conserved Energy
CCO ₂	Specific CO ₂ Mitigation Cost
CCS	Carbon Capture Storage
USGV	United States Geological Survey
EERE	Energy Efficiency and Renewable Energy, US Department of Energy
ICARUS-4	Data Base of Technological Options of Energy Savings for all Economic Sectors in the Netherlands
FE	Frozen Efficiency Scenario
BAU	Business as Usual Scenario

Energy Units

kilo (k) = 10³

mega (M) = 10⁶

giga (G) = 10⁹

tera (T) = 10¹²

peta (P) = 10¹⁵

1 Btu = 1,055.056 J

Carbon Dioxide (CO₂) Emission Factors¹:

Natural Gas= 0,056 tCO₂/GJ

Coal= 0,095 t CO₂/GJ

Oil= 0,077 t CO₂/GJ

Global Warming Potential (GWP) (t = 100yr):

CO₂ = 1 N₂O = 310²

1 "Introduction to Energy analysis", Kornelis Blok (page 141)

2 <http://www.epa.gov/nitrousoxide/index.html>

1 Introduction

Food production is a main issue in the contemporary society. The major concern is how to produce food to feed the world population. The International Energy Agency (IEA) predicts an increase in population from 2005 up to 2030 of 20% (or 40% since 1995 Figure.1.1 (FAO 2003)). Due to a diet shift: it is expected that people will eat more meat from now on and in order to produce meat it is required extra production of cereals to feed the animals (cereal production will increase 50%). However, the increase on arable land (7%) is not coping with the overall demand and consequently there will be higher pressure on the fertilizer sector (predictions indicate 60% increase in demand) (FAO 2003).

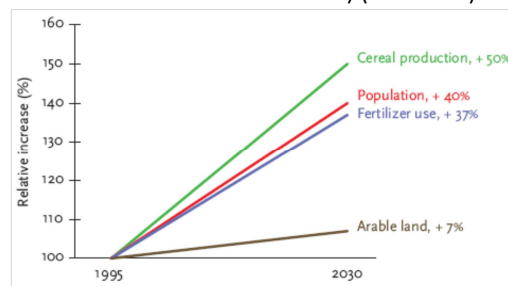


Figure 1.1: Projected development of cereal production, global population, fertilizer use and arable land (FAO 2003).

The International Fertilizer Industry Association (IFA) reports a contribution of 0,93% in GHG (465 Mt CO₂-eq), mainly carbon dioxide (CO₂) and nitrous oxide (N₂O), released by the fertilizer production sector (IFA 2009). Focus on improving the production sector of fertilizers, in terms of energy savings and emission reduction, is mandatory to sustain a balanced planet and meet the Kyoto Protocol targets proposed by United Nations Framework Convention on Climate Change (UNFCCC).

Fertilizers contain mostly nitrogen (N) and also phosphorous (P) and potassium (K). This research will focus on the production process of nitrogen fertilizers, in particular in the production of ammonia (the most abundant fertilizer produced) and in a less extent urea and nitric acid fertilizers.

Ammonia fertilizer is largely used to produce other fertilizers (Figure 1-2 below). It is conceived by combining nitrogen from the air and hydrogen. Hydrogen can be produced from natural gas, naphtha or refinery gas using the steam reforming process or from coal, coke, heavy hydrocarbon fractions applying the partial oxidation process or even from water using the water electrolysis process.

The output is generally ammonia, sulphur (which in partial oxidation is recovered in a Claus unit), steam (although this also differs according to the process), carbon dioxide (CO₂) and nitric oxide. To reduce the energy consumption and lower carbon dioxide and nitric oxide emissions, investments in developed processes and revamp of the plants should be made.

The most used nitrogen fertilizer in the world is urea. The biggest demand is in Asia due to its application on flooded rice agriculture. Urea is produced by the reaction of ammonia and carbon dioxide at high pressure forming an intermediate compound the ammonium carbamate. Applying heat, the compound is then dehydrated forming urea and water. In most of the cases ammonia and urea plants are built together since urea can directly use ammonia and carbon dioxide released on the ammonia process. It saves energy and it reduces carbons dioxide emissions of both processes.

Nitric acid is not used as a fertilizer. It is an intermediate product that is combined with other compounds to form important fertilizers such as ammonium nitrate (Figure 1.2). The production of nitric acid occurs in two steps: first - the oxidation of ammonia producing nitric oxide, water and nitrous oxide (N₂O) by-product and second - the oxidation of nitric oxide and absorption in water. The production of N₂O is a

major concern because N_2O emissions contribute 310 times more in terms of global warming potential (GWP) than CO_2 .

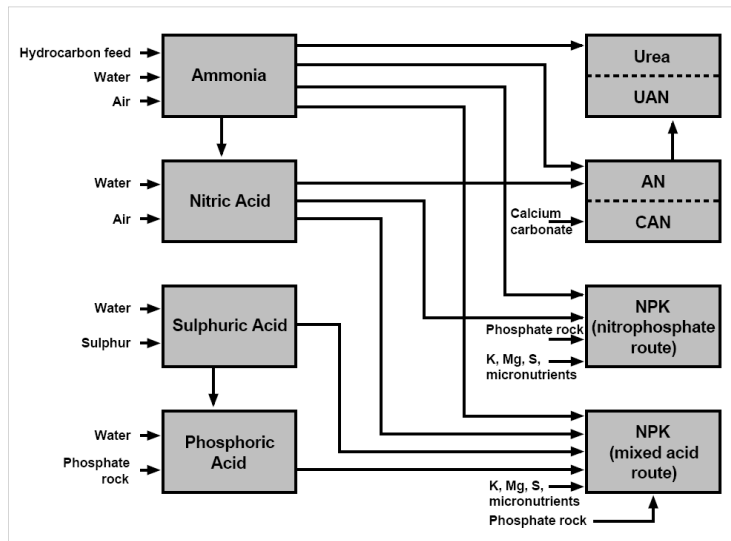


Figure 1.2: Fertilizer production routes (EFMAa, 2000).

Currently, the production of nitrogen ammonia fertilizer occurs in China, India, Russia and United States accounting for 55% in the overall production (Figure 1.3).

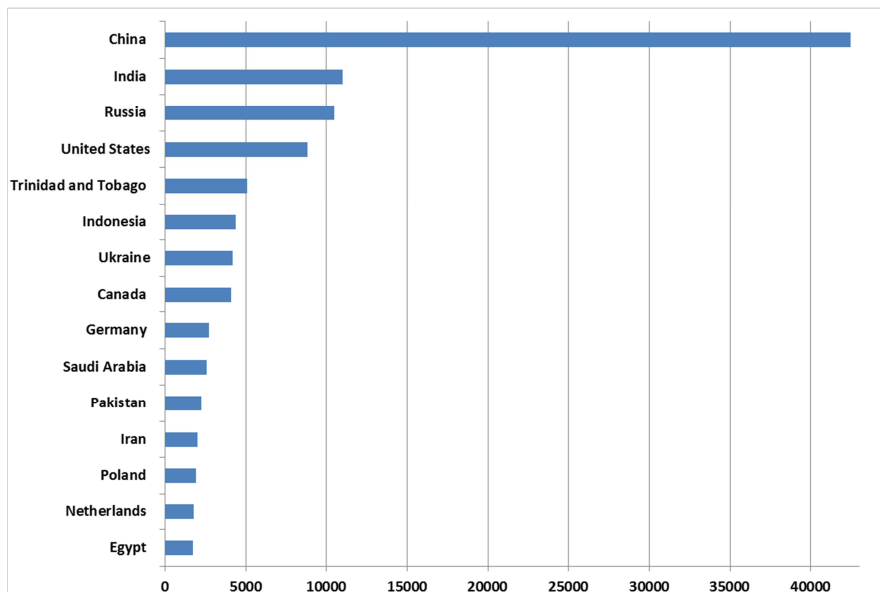


Figure 1.3: Main countries producing ammonia fertilizer in 2007 (USGS 2009).

Significant energy savings and emission reduction are achievable if improvements on the production techniques of these three fertilizers are applied, either implementing Best Practice Technology (BPT) or Best Available Technology (BAT). For instance, the International Energy Agency (IEA) reports that about 1 EJ (20%) would be saved if best available technology were applied in ammonia production. The International Fertilizer Industry (IFA) mentions that globally the energy savings potential of ammonia facilities, based on natural gas, could reach around 15%; in addition the overall potential for reducing

greenhouse gases emissions (accounting carbon dioxide and nitrous oxide emissions) could reach more than 25% (and possibly as much as 40% if BAT becomes the norm).

In synthesis, the production of each fertilizer involves different raw materials, it has associate different energy consumptions levels and it releases different GHG emissions. The main issues addressed on this research are presented in Table 1.1.

Raw material	Production of	Major issues
Hydrocarbon feed, water, air	Ammonia	Energy consumption CO ₂ emissions
Ammonia, carbon dioxide	Urea	Energy consumption CO ₂ emissions
Air, Ammonia	Nitric Acid	N ₂ O emissions (or CO ₂ equivalent emissions)

Table 1.1: Overview of the raw materials and the major issues concerning nitrogen fertilizers.

Research objective

According to the agreement settled by the European Commission to reduce carbon dioxide and nitrous oxide emissions (or carbon dioxide equivalent), the nitrogen fertilizer industry should become more efficient and less polluting. The aim of this survey was to study its global abatement potential. Therefore investigation concerning the technology available to reduce global carbon dioxide emissions equivalent was made allowing the construction of carbons dioxide abatement curves. A global perspective of the present and future situation is presented. This study focus mainly on ammonia production; urea and nitric acid production survey is briefly mentioned.

Research question:

What is the global GHG abatement potential of the nitrogen fertilizer industry up to 2030?

Sub-questions:

- What is the baseline energy use and intensity in nitrogen fertilizer industry of the major nitrogen producing countries that make up 80% of global production?
- What are the baseline GHG emissions and intensities of the major nitrogen producing countries?
- What is the current status of technology in nitrogen fertilizer sector of these countries?
- What are the technological options to reduce GHG emissions in nitrogen fertilizer sector that are currently commercially available or will be within the next 20 years (up to 2030)?
- What is the implementation potential and what are the GHG emissions reductions of the different technological options in the different countries?

The survey's concept is to develop GHG abatement curves. Accordingly, a study for the major producers of nitrogen fertilizers, covering 80% of the total production is investigated. The top 15 larger producers of the ammonia fertilizers are: China, India, Russia, United States, Trinidad and Tobago, Indonesia, Ukraine, Canada, Germany, Saudi Arabia, Pakistan, Iran, Poland, Netherlands and Egypt as seen in Figure 1.2. The time frame ranges from 2005, defined as base year, up to 2030. Required assumptions are mentioned when lack of data was verified. This review does not intend to generate policy scenarios regarding the GHG emission reduction.

2 Nitrogen fertilizer industry

On this second chapter the aim is to contextualize the importance of nitrogen fertilizer industry in terms of its production trends when compared to other industrial fertilizers, and also to demonstrate the importance of ammonia fertilizer in the nitrogen fertilizer sector.

2.1 Historical trends of nitrogen fertilizer consumption

Nitrogen fertilizer demand has been increasing in the last decades. Figure 2.1 depicts the consumption trends of three types of fertilizers: Nitrogen (N), Phosphate (P) and Potassium (K). Since 1970, the nitrogen fertilizer consumption had been scaling up compared to other fertilizers and consequently the gap between nitrogen consumption and the other two fertilizers increased. Yara (2008) predicts that the growth rate for nitrogen consumption will increase by 3,2 % on average per year.

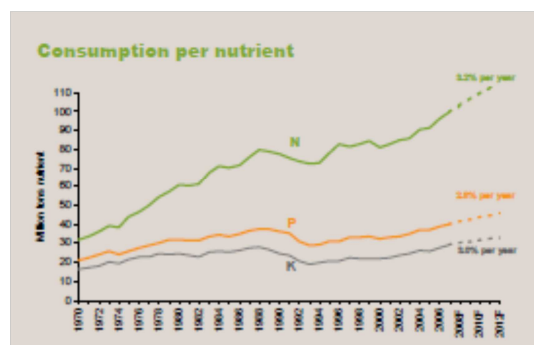


Figure 2.1: Fertilizer consumption per nutrient (Yara 2008).

2.1.1 Historical production trends of ammonia and urea

Yara's report from 2008 provides data regarding ammonia and urea production since 1998. In Figure 2.2 shows the production trends of both fertilizers:

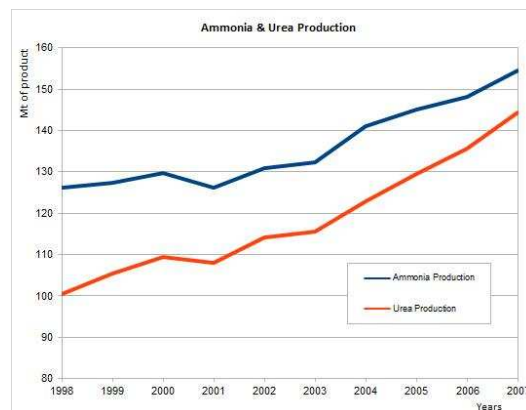


Figure 2.2: Ammonia and urea production (Yara 2008)

In 2007, ammonia production reached 154.7 million tons, an increase of 1.3% compared to the previous year regardless the average growth rate per year of 2,3%. Urea's situation is different: the production in 2007 was 144,1 million tons with an increase of 6,5 % compared to last year and the average growth rate is 3,8 %. In the case of urea, the main consumers are also the major producers specifically China and India. Most of the new nitrogen capacity in the world is urea, due to urea's high nitrogen content (46%) and relatively cheap transport; demand growth is to a large extent taking place in climates which favour its use

(Yara 2008). Therefore production and consumption growth rates for urea are higher than for ammonia in terms of nitrogen content.

2.1.2 Historical production trends of N₂O emissions due to nitric acid production

Data concerning nitric acid production for 2005 or any other years was not available. The BREF reports nitric acid production for a few European countries in 2003 but that was not enough to cover the aim of this research because it includes other countries beyond the European Union. To round this problem a solution was adopted. Rather than collecting nitric acid production data, the focus was on searching for information regarding N₂O emissions released on the manufacturing of nitric acid itself. Ramirez et al (2003) presents a graph depicting the N₂O concentration in the atmosphere in the last millennium.

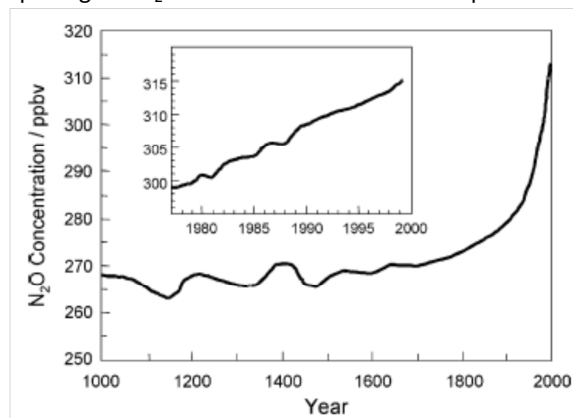


Figure 2.3: Evolution of the atmospheric N₂O concentration (Ramirez et al 2003).

Figure 2.3 shows that N₂O has been relatively constant in the previous centuries (270 ppbv). The situation has changed in the last decades and nowadays N₂O concentration reaches 310 ppbv; it represents a 9% increase when compared to pre-industrial levels (285 ppbv). The annual growth rate is 0.2–0.3% (Ramirez et al 2003).

Generally, N₂O is released to the atmosphere via natural and anthropogenic sources. Ramirez et al presents a detailed table discriminating each N₂O type of source and the correspondent weigh (Table 2.1). From this table it is possible to calculate that N₂O emissions due to nitric acid production represent 2 % of the global N₂O emissions released (0,4 out of 20 Mt N₂O per year). IPCC 2001 states that N₂O concentrations on the atmosphere increase by 16% since 1750 due to anthropogenic reasons (IPCC Technical Summary, 2001). Ramirez et al (2003) states that efforts must be performed to decrease N₂O emissions on the industrial sector because the techniques are rather easy to implement on a short term basis and have a quite large impact on the emission reduction.

Type of source	N ₂ O emissions (Mt N ₂ O per year)
Natural	~13
Soils	10
Oceans	2,9
Atmospheric chemistry	0,2
Anthropogenic	~7
Agriculture (including fertilizers)	3,5
Nitric Acid production	0,4
Adipic Acid production	<0,1
Fossil fuel combustion (stationary)	0,2-0,5
Fossil fuel combustion (mobile)	0,4-0,9
Biomass combustion	1,0
Sewage tretment	1,5
Total of all sources	~20

Table 2.1: Global N₂O emissions (Ramirez et al 2003).

Nitric acid is an inorganic compound used primarily to make synthetic commercial fertilizer. The raw material is used on a large extent for the production of adipic acid but also to produce explosives, metal etching and in the processing of ferrous metals. Adipic acid is a white crystalline used for the manufacturing of nylon, low temperatures lubricants, synthetic fibers, coatings, plastics, etc. Although global adipic acid demand is expected to increase, N₂O emissions from this source (see table 2.1 above) are expected to decrease substantially. The abatement technologies considered for N₂O emissions reduction due to adipic acid production range from 90-99% efficiency. Most of them were implemented in the end of the eighties and since then adipic acid is no longer the major source of N₂O emissions for the industrial sector like it used to be.

2.2 Ammonia's relevance and characterization

Among all the nitrogen fertilizers, ammonia is most important fertilizer of the nitrogen fertilizer industry. It is the source of nearly all the synthetic nitrogen fertilizers produced in the world. It is produced in industrial scale by combining nitrogen in the air with hydrogen from hydro carbonates, under high temperatures and pressures and in the presence of catalysts.

The production of ammonia can be obtained by different processes and from different hydrocarbons sources but the most common is to use the steam reforming process and natural gas as feed stock. Natural gas has the highest hydrogen content of any existing energy source, which makes it highly desirable as a source of hydrogen for ammonia synthesis. When natural gas is oxidised it releases less tonnes of CO₂ per energy unit and it requires less energy per unity of ammonia produced. As a reference a typical heavy-oil-based process uses 1.3 times more energy than a gas-based process; and a coal-based process uses 1.7 times more energy than a gas-based process.

Ammonia is largely produced where natural gas is a main resource and consequently cheaper than in other countries. However, the use of natural gas as a feedstock has been changing in the last decades. Table 2.2 shows how the feedstock share is evolving in the last 20 years:

Feedstock	Process	% of world capacity			
		(1990) (BREF 2006)	(2000) (Nand 2004)	(2006) (IEA 2009)	(2008) (IFA 2008)
Natural Gas	Steam reforming	77,0%	73,0%	71,0%	67,0%
Coal	Coal gasification	13,5%	16,0%	21,0%	27,0%
Naphta	Steam reforming	6,0%	4,0%	0,0%	2,0%
Other Petroleum products	Partial oxidation	3,0%	6,0%	9,0%	3,0%
Water	Water electrolysis	0,5%	0,0%	0,0%	0,0%
Others	Partial oxidation	0,0%	1,0%	0,0%	1,0%

Table 2.2: Applied processes and feedstock of ammonia's production.

On table 2.2 is illustrated that the use of natural gas as a feedstock have been decreasing in the last years and a significant increase in coal ammonia capacity have been emerging. This is justified by China's grow demand of ammonia capacity and the lack of natural gas as a resource. China uses mainly coal to produce ammonia.

Naphtha feedstock has been decreasing while other petroleum products remain constant over the years. The authors in 1990 and 2008 presented numbers based on different definitions: in 1990 the author presents naphtha including LPG and refinery gases; in 2006 and 2008 the "other petroleum products" are only referring to oil. The figures concerning this feedstock are not very coherent and are not taken as a reference.

Figure 2.4 shows how much certain countries like China and India are contributing to the global share of ammonia capacity.

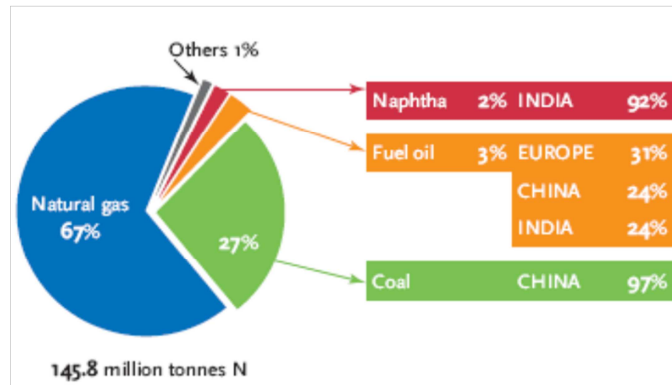


Figure 2.4: Global ammonia capacity by feedstock 2007 (IFA 2008).

It confirms that China is leading the ammonia production based on coal. India is the top ammonia producer using naphtha as a feedstock, but its global share is nowadays quite insignificant. The share of feedstock concerning fuel oil is more or less equally shared between Europe, China and India. Although in global terms fuel oil is not representative.

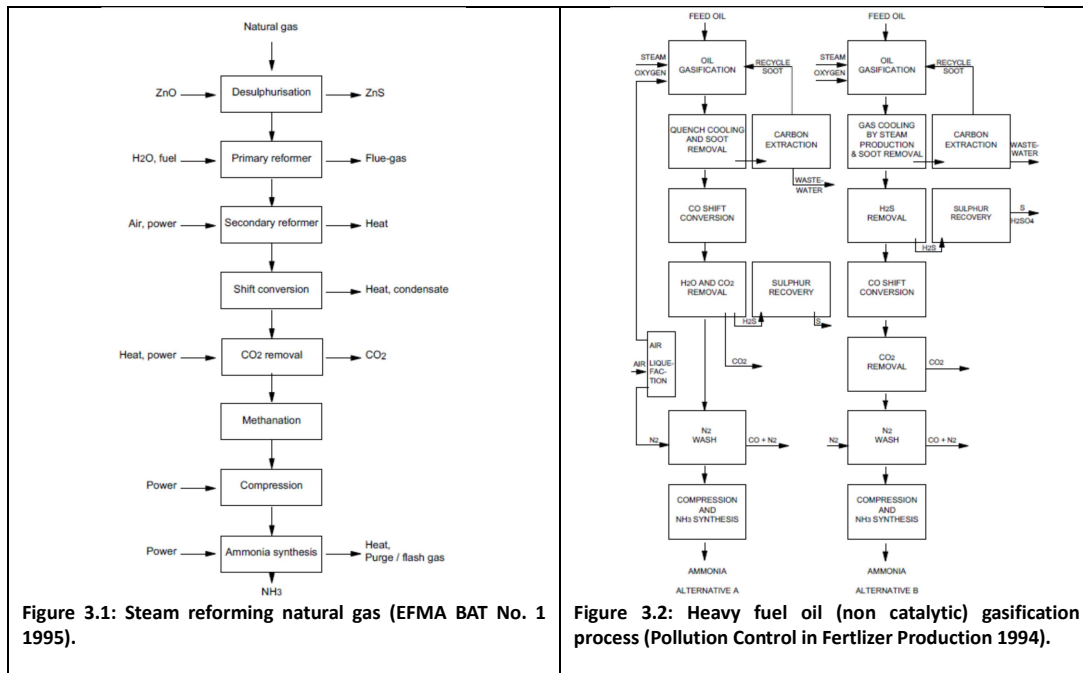
3 Outline of the processes

In this chapter a general description of the processes involved in the production of ammonia, urea and nitric acid are presented.

3.1 Ammonia process

The capacity of a typical modern ammonia plant ranges from 1000–2000 t/day. New ammonia plants are now being design to produce up to 3000 t/day (EFMAa 2000). An ammonia plant is a highly integrated process: the distribution of energy over fuel and feedstock is somehow arbitrary and is partly determined by the operating conditions. Ammonia plants are usually coupled with other plants, particularly with urea plants.

The most common process used to produce ammonia is the steam reforming based on natural gas. Nevertheless, partial oxidation processes using heavy fuel oil, residual oils or coal are also an alternative. It depends on the availability and/or cost of the various feedstock and oxygen. Typical processes using natural gas, oil and coal are depicted in figures 3.1 to 3.4. There are several variations.



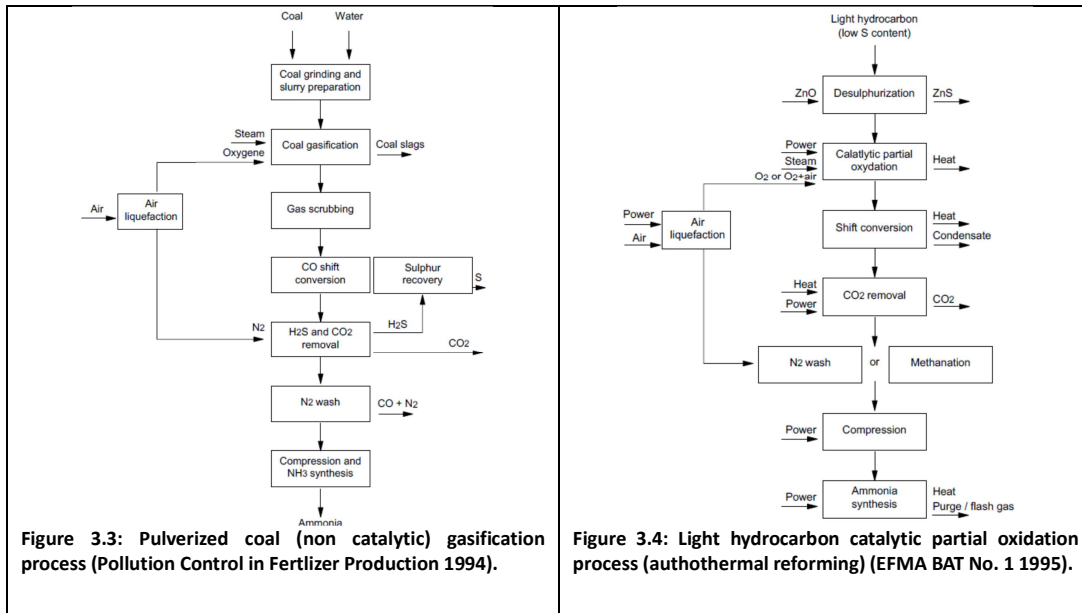
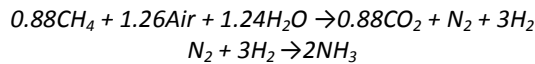


Figure 3.3: Pulverized coal (non catalytic) gasification process (Pollution Control in Fertilizer Production 1994).

Figure 3.4: Light hydrocarbon catalytic partial oxidation process (autothermal reforming) (EFMA BAT No. 1 1995).

Figure 3.5: Diagrams are presented in UNEP 2000.

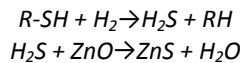
The theoretical conversion process, based on methane feedstock, is the following:



The steam reforming process involves several steps that will be described in detail. They follow the figure 3.1 above.

3.1.1 Desulphurisation

The natural gas mix that arrives through the pipelines to the ammonia plants contains sulphur compounds. They must be removed from the mixture otherwise they poison the catalyst process. Thus the first step is to remove them from the feed-gas by heating the mixture to 350-400°C; the second step, is to hydrogenate the sulphur compounds to H₂S in a desulphurization vessel, typically using a cobalt molybdenum catalyst and the adsorbed on pelletized zinc oxide:



3.1.2 Primary Reformer

The mixture, now essentially natural gas, is heated to 500-600°C and introduced together with steam in the primary reformer. In the new plants or on revamped plants, the pre-heated steam/gas mixture is passed through a pre-reformer and re-heated in the convection section before entering the primary reformer. The primary reformer contains a large number of high-nickel chromium alloy tubes filled with nickel-containing reforming catalyst. The overall reaction is highly endothermic and additional heat is required to raise the temperature to 780-830°C at the reformer.

The chemical reactions in the primary reformer are:



The applied steam to carbon ratio (S/C ratio) is typically around 3,0. Though, the optimum ratio depends on: feedstock quality, purge gas recover, primary reformer capacity, shift operation and plant steam balance. The optimum S/C ratio in new plants is lower. The heat for the primary reforming process is supplied by burning natural gas or other gaseous fuels in the burners of a radiant box containing the tubes. (the amount of sulphur in natural gas is usually small enough to avoid the need for desulphurisation of the fuel-gas, but if it is required to meet local emission standards, then the gas supply is entirely

desulphurised). The temperatures of the flue-gases leaving the radiant box exceeds 900°C, after supplying the necessary high level heat to the reforming process (700-850°C). However, only 50-60% of the fuel's heat value is directly used in the process itself. The heat content (waste heat) of the flue-gas is used in the reformer convection section for steam system demands and other processes. The flue-gas leaving the convection section at 100-200°C is the main source of emissions of the plant, releasing CO₂, NO_x and small amounts of SO₂ and CO.

3.1.3 Secondary Reformer

Only part of the hydrocarbon feed is reformed in the primary reformer (EFMAa 2000 refers 30-40%, UNEP 2000 mentions 40- 50%). In order to increase this result a secondary reformer is required. The products from the primary reformer go into a secondary reformer where the gas is mixed with pre-heated air and a nickel catalyst at 1100°C. Natural gas is burned to provide enough energy for the reaction to occur. In some cases excess air is supplied to the secondary reformer in order to reduce the duty of the primary reformer (smaller size) and milder the reforming conditions (Worrell& Blok 1994). Up to 99% of the original feed-gas is now converted. The final products are further cooled to 350-400°C in a waste heat steam boiler.

3.1.4 Shift conversion

The final products from the secondary reformer contain a range of 12 to 15% of CO (dry gas base). To reduce CO concentration this one is combined with H₂O producing CO₂ and H₂ according to the reaction:



The reaction occurs in the two stage converters, using the water-gas shift reaction. It involves the use of iron-chromium at the high temperature stage (350-400°C) or the use of copper-zinc at the low temperature stage (200-240°C). In practice, the high-temperature and the low-temperature catalyst are used in series. The heat released during the reactions is recovered during the cooling between the catalyst beds. In the end, the gas contains approximately 0,2-0,4% CO(dry gas base) (EFMAa 2000) and 18% CO₂ (Worrell&Blok, 1994). It is important for the process efficiency to reach low amounts of CO.

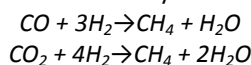
3.1.5 CO₂ removal

The gas contains mainly H₂, N₂, CO₂ and excess steam from the previous process. Most of the excess steam is condensate before it enters into the CO₂ system removal. An energy-efficient CO₂ removal system should require a low heat demand. The CO₂ is removed either by a chemical or a physical absorption process. In the chemical absorption process the solvents used are aqueous amine solutions: Mono Etlanolamine (MEA) Activated Methyl DiEthalomine (aMDEA) or hot potassium carbonate solutions. In the physical absorption process the solvents used are glycol dimethylethers (Selexol), propylene carbonate and others (EFMAa 2000).

The techniques regarded as BAT and currently implemented in new ammonia plants are: Activated Methyl DiEthalomine (aMDEA) or similar, Benfield process (HiPure, LoHeat), or similar; and Selexol or similar physical absorption processes (EFMAa 2000). Pressure Swing Adsorption (PSA) technique is indicated as an emerging technique. It combines in one step the CO₂ removal process with the methanation (next process).

3.1.6 Methanation

Although the main components of the gas are now N₂ and H₂ there are still residual concentrations of CO₂ and CO that can poison the next processes and for this reason they must be removed. CO and CO₂ are converted in CH₄ by hydrogenation (using a nickel catalyst bed at 300°C). CH₄ does not harm the synthesis catalyst but the water formed does, thus it is removed by further techniques.

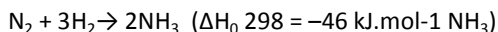


3.1.7 Compression

Centrifugal compressors are used in ammonia plants to pressurize the gases until a certain level (100-250 bar, 350-550°C) suitable for the next step: the synthesis process. After the first compressor stage, molecular sieves are used to remove the last traces of H₂O, CO, and CO₂. The compressors are usually driven by steam turbines utilizing steam produced from the excess process heat.

3.1.8 Ammonia synthesis

The last process takes place on an iron catalyst at pressures usually in the range of 100-250 bar and temperatures of 350-550°C. The reaction is:



Only 20-30% of the synthesis gas is converted per pass to ammonia, due to unfavorable equilibrium conditions. The unreacted gas is recycled after removing the ammonia formed. Fresh synthesis gas is supplemented in the loop (BREF 2006). The synthesis gas contains unreacted gases and also inerts (methane and argon). In order to prevent their accumulation, a continuous purge gas stream is added. Therefore, purge gas basically contains ammonia, nitrogen, hydrogen, inerts and unreacted gases keeping it in a level of 10-15%. The purge gas is scrubbed with water to remove ammonia, before then being used as fuel or before being sent for hydrogen recovery (BREF 2006).

In general, to increase efficiency and decrease emissions of the ammonia production process, UNEP suggests that the future developments must focus on: lowering the steam/carbon ratio; increasing the conversion share of the secondary reformer; improving the purification of the synthesis gas and improving the power energy system. The new techniques are going towards this direction: introduce excess air on the secondary reformer; input O₂ enriched air to the secondary reformer and set a heat exchange autothermal reforming (UNEP 2000).

The other feedstocks, besides natural gas, like heavy fuel oil and coal contain significant amounts of sulphur. Thus, partial oxidation gasification is non-catalytic and occurs at high pressure and high temperature. Pressures exceed 50 bar, and temperatures are around 1400°C. Steam is added to moderate the temperature. To supply oxygen and nitrogen an air separation unit is required. In comparison with the heavy fuel oil process, coal gasification is slightly more complex requiring extra steps like: coal grinding and preparation of slurry for pulverization and the addition of coal slags (Figures 3.2-3.3).

The simplest process occurs using a feedstock that has light hydrogen content and low sulphur content (naphtha, L.P.G., methane). In this case partial oxidation is catalytic. Pressures are not limited by metallurgical problems (Figure 3.4). Detailed information about ammonia production processes can be found in BREF 2006, UNEP 2000, EFMAa 2000.

3.2 Urea process

Urea is produced in two steps: $2\text{NH}_3 + \text{CO}_2 \rightarrow \text{NH}_2\text{COONH}_4 \rightarrow \text{CO}(\text{NH}_2)_2 + \text{H}_2\text{O}$

First, ammonia reacts with carbon dioxide. The reaction is fast and exothermic; it goes to completion under the conditions used industrially. Both, CO₂ and NH₃, arrive directly from the ammonia plant. In this first step, carbamate (NH₂CO₂NH₄) is synthesized. The conversion (on a CO₂ basis) is usually in the order of 50-80%. The conversion increases, elevating temperature and NH₃/CO₂ ratio; and it decreases, lowering H₂O/CO₂ ratio. Second, the carbamate is dehydrated to urea. The reaction is slow and endothermic and does not go to completion. Thus NH₃ and CO₂ are stripped from the urea solution and recycled.

The design of commercial processes is focus on how to separate the urea from the other constituents, how to recover excess NH₃ and how to decompose the carbamate for recycle. Additionally researched is being developed on materials to withstand the corrosive carbamate solution and to optimize the heat and energy balances.

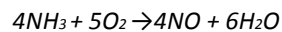
Originally, the first urea plants in operation used a once through principle where the off-gases were used as feedstocks for other products. The evolution of technology brought up another process called partial

recycle, where part of NH₃ and CO₂ was recovered and recycled back into the process. Later on, the total recycle process was developed; this involves cooling the gases and re-combining them forming carbamate liquor which is pumped back to the synthesis. A series of loops involving carbamate decomposers at progressively lower pressures and carbamate condensers are used. This process increase NH₃/CO₂ molar ratio and consequently increases urea yield. Afterwards, significant improvements were made by decomposing the carbamate in the reactor effluent without reducing the system pressure using the stripping process. Two commercial stripping systems were developed, one using CO₂ and the other using NH₃ as stripping gases. Nowadays other processes have emerged that combine the best features of total recycle and stripping technologies. (EFMAb 2000)

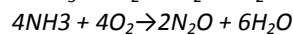
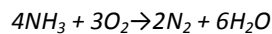
After producing urea solution, there are several techniques to dry it but usually the solution is treated in a prilling tower producing granulate. New urea installations vary in size from 800 to 2,000t.d-1, but their size is typically 1,500t.d-1 units (EFMAb 2000). Modern processes have similar energy requirements and nearly 100% material efficiency. UNEP 2000 suggests as a BAT for urea production: carbons dioxide stripping process, ammonia stripping process, advanced cost and energy saving (ACES) process and isobaric double recycled (IDR) process.

3.3 Nitric Acid process

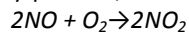
The production of nitric acid is made up in three steps (UNEP 2000). The first step is the oxidation of ammonia forming nitric oxide and water:



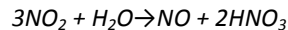
At the same time nitrogen and nitrous oxide are formed:



The nitrous oxide (N₂O) is an undesirable by-product; the second step is the oxidation of the nitric oxide (NO):



On the third step the mixture passes through an absorber column producing HNO₃ (reaction with water):



The total process is highly exothermic, so waste heat boilers are installed to generate superheated high pressure steam. There are two main types of processes in use: the single-pressure (oxidation and absorption occur at the same pressure); and dual-pressure (the absorption occurs at a higher pressure than oxidation). For both types a large number of different processes (with different operating pressures: low, medium (3-7 bar), high (<8 bar)) have been developed (EFMA 2000c). The most common types of plants in Europe are medium/high pressure plants.

4 Nitrogen production process: energy consumption and GHG emissions

Fertilizer production consumes 1.2% of the world's total energy on an annual basis (IFA 2009). It is also one of the industry's main sources of GHG emissions: 465 Mt CO₂-eq (0,93% of the world share of GHG) (IFA 2009). Nitrogen fertilizers contribute to produce up to 50% of the food grown worldwide (IFA 2009); though, their production is energy-intensive due to the ammonia synthesis from which 99% of all nitrogen fertilizers are derived (IFA 2009). The energy consumption of ammonia production represents 87% of the nitrogen industry's total energy consumption. Only about 20% of the ammonia manufactured is orientated to industrial uses and not part of the agricultural life cycle (IFA 2009). In the next paragraphs the energy consumption and the GHG emissions involved in the production process of each fertilizer is going to be described.

4.1 Ammonia production process: energy consumption and CO₂ emissions

Ammonia is part of the chemical and petrochemical industry sector. In 2004, the chemical and petrochemical industry consumed 34 EJ, which represents 30% of total global industry final energy use (IEA 2008). Ammonia represented 22% of the total energy used in the chemical and petrochemical industry; just followed by ethylene, ammonia is the second highest energy intensive chemical to produce (24%)(see table 4.1).

	Amount	LHV	Feedstock Energy Needed	Fuel		Total Fuel + Feedstock
	Mt/ yr	GJ/t	EJ/yr	GJ/t	EJ/yr	EJ/yr
Ethylene	103,3	47,2	4,9	13	1,3	6,2
Ammonia	140,0	21	2,9	19	2,7	5,6
Total			17,0		8,2	25,2

Table 4.1: Energy use in the Chemical and Petrochemical Industry 2004 (Excluding Electricity)(IEA 2008).

Raw materials, such as natural gas or coal, are called feedstocks when used in the manufacturing process. In the case of ammonia, the fraction of the energy that refers to the feedstock, accounts for more than half of total energy use to produce it (Table 4.1). The energy used for feedstock cannot be reduced through energy efficiency measures. In 2004, total energy and feedstock use for ammonia production amounted to about 4.3 EJ of natural gas, 0.6 EJ of oil and 1.2 EJ coal (IEA 2007). A 30% decrease in energy use per tonne of ammonia has been achieved in the last thirty years (IEA 2007).

Nowadays, the energy efficiency of natural gas-based ammonia plants tends to converge while newer plants have similar efficiencies across regions. The implementation of advanced techniques and technologies improve energy efficiency and waste management and provide emissions reduction. There are several articles reporting energy savings measures in ammonia plants. They include improvements in the reforming section, such as the use of gas-heated reformers that offer smaller surface areas and heat loss; the use of membranes for hydrogen separation; advanced CO₂ removal technologies; developments in ammonia separation and in ammonia synthesis (Rafiqul, 2005).

The International Fertilizer Industry Association reported a benchmarking survey comparing the energy efficiency of 66 ammonia production plants (not including China) with ages from one to thirty-five years (IFA, 2006). The results of this study show that, the average energy use of the ammonia plants is 36.9 GJ/t, and it ranges is from 28 – 53 GJ/t of ammonia (it excludes plants in China). In general, the plants with the highest capacity have the best efficiency in contrast with older plants (20+ years) that have 8 – 10 % lower efficiencies (IFA, 2006).

As previously mention, the aggregated CO₂ emissions due to ammonia production depend on the type of hydrocarbon used as well as the technologies adopted. However, as a reference, for natural gas-based ammonia production, one-third of emissions are associated with the burning of fuel and two-thirds with the use of fossil fuel as a feedstock to obtain the hydrogen needed to synthesize ammonia. In coal-based

ammonia production, the proportions differ slightly: 25% and 75% respectively (IFA 2009). The energy consumption and the CO₂ emissions associated with the consumption of feedstock are subject to the laws of chemistry; the modern plants are close to reach the theoretical minimum concerning the energy consumption and the CO₂ emissions (IFA 2009). Different numbers are suggested by several authors regarding the theoretical minimum of energy consumption and specific energy consumption (SEC) for best available technique (BAT) of ammonia manufacture using natural gas (table 4.2). The SEC BAT for Nieuwlaar 2001 is considered too optimistic; the one suggested by IFA 2009 is used as a reference in this research.

Steam reforming process using Natural Gas	Blok & Worrell (1994)	Rafiqul et al. (2005)	IEA (2007)	Nieuwlaar (2001)	IFA (2009)
Theoretical minimum energy consumption	19.1 GJ/ton NH ₃ (LHV)	19.4 GJ/t NH ₃ (LHV)	21,2 GJ/t NH ₃ (LHV)	(not mentioned)	20,0 GJ/tNH ₃ (LHV)
Best Available Technology (natural gas)	28,0 GJ/ton NH ₃ (LHV)	28,0 GJ/ton NH ₃ (LHV)	28,0 GJ/t NH ₃ (LHV)	26,1 GJ/t NH ₃	27,0 GJ/ton NH ₃ (LHV)

Table 4.2: Data collection of the theoretical minimum and Best Available Technology of SEC of ammonia production.

The use of pure CO₂ obtained from the steam reforming process and the amount of CO₂ reused in the urea production or other purposes, affect the CO₂ balance of ammonia production. Rafiqul et al presents (table 4.3) the CO₂ emissions for different technologies in various countries. In the past decades, energy efficiency measures that lead to significant reduction in terms of CO₂ emissions have been implemented. On average, the European ammonia plants release 2.2 t CO₂/t NH₃, while 30 years ago the net CO₂ emission was around 2.7 t CO₂/t NH₃. At BAT levels the energy consumption reference is 28 GJ/t with an emission factor of 1.56 t CO₂/t NH₃(Rafiqul 2005).

Fuel used	Technology	Year	Country/region	SEC (GJ/t NH3)	Emission factor (g CO ₂ /MJ)	CO ₂ (t/T NH ₃)
Natural Gas	Steam reforming	1994-1996	US	41,3	55,7	2,3
	Steam reforming	1994-1996	EU	34,9	55,7	1,9
	Steam reforming	1994-1995	India	38,7	55,7	2,2
Heavy fuel oil	Partial Oxidation	1994-1995	India	59,8	78,6	4,7
Coal	Partial Oxidation	1991-1992	India	165,9	100,7	16,7

Table 4.3: Data collection presented by Rafiqul 2005.

The benchmarked study from IFA 2008 states that CO₂ emissions range from 1.5-3.1 Mt CO₂/Mt ammonia. The average CO₂ emissions were 2.1 Mt CO₂ /Mt of ammonia. According to the same report 36% of the CO₂ produced in 2008 was recovered. About one-third of the CO₂ generated globally was captured for production of urea. The remaining CO₂ captured by the fertilizer industry (2.2%) was sold for other value chains, e.g. to the oil and gas industry (for injection into wells) or to the beverage industry. Enhanced oil and gas recovery is the only current downstream use of the ammonia sector's CO₂ that qualifies under the term "Carbon Capture and Storage" as used in climate change policy discussions. CO₂ captured for urea production, or for use in beverages and other downstream products, is released to the atmosphere later in the value chain. When more CO₂ is produced than can be reused on-site or sold, the balance is vented to the atmosphere.

4.2 Urea production process: energy consumption and CO₂ emissions

In most ammonia plants, CO₂ is separated from hydrogen at an early stage. Much of this CO₂ separated is used to produce urea. It takes 0.733 tonnes of CO₂ to produce a tonne of urea (IEA 2007). In a modern total 'recycling' urea process, conversion of ammonia to solid urea requires 3.3 GJ/t Urea (Kongshaug 1998); the OECD/IEA (2009) report suggests BTP is 2.5 GJ/t Urea and IFA 2009 suggests 3,20 GJ/t Urea. IEA follows the methodology of the Intergovernmental Panel on Climate Change (IPCC) according to which emissions are accounted on the sector where they occur. Meaning that the CO₂ emissions from ammonia

production and used on urea production are discounted. Therefore the CO₂ emissions from the decomposition of urea are taken into account only in the agricultural sector. In a worldwide scale about 100 Mt of CO₂ is used per year for urea production (2007) and the sequestered amount of it is released again on the land field, but that emissions belong to the agricultural sector (OECD/IEA 2009).

4.3 Nitric Acid production process: energy consumption and N₂O emissions

4.3.1 Energy consumption

As previously mentioned, the overall process of producing nitric acid is highly exothermic. New designs of nitric acid plants are being developed focusing on lowering the steam consumption (due to the incorporation of expansion turbines) and/or which have increased heat recovery producing electricity. ECN 2009 presents the evolution of the net export energy in the last decades (Figure 4.1). A modern dual pressure nitric acid plant has a net export of 11 GJ/t N, although the average net export for European plants is 7 GJ/t N (ECN 2009).

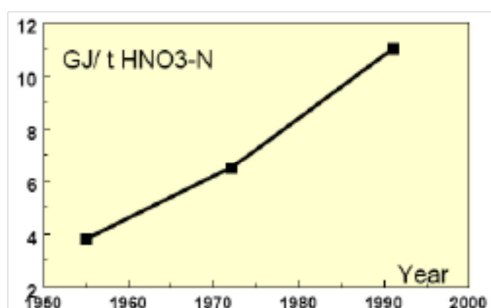


Figure 4.1: Net export of Nitric Acid plants (GJ/t HNO₃-N) (Kongshaug 1998; Wisenberger 2001)

A net export of energy is not verified in all the nitric plants of the world, but even when that do not occurs the energy required is not significant. Therefore the energy consumption of nitric acid plants is not part of the scope of this report.

4.3.2 N₂O emissions

Nitric acid production represents the largest source of N₂O in the chemical industry, with a global annual emission of 400 kt N₂O (Ramirez et al 2003). Generally, N₂O emissions released from nitric acid plants are grouped by the process used: low pressure plants emit on average 5kg N₂O/t nitric acid; medium pressure plants emit 7kg N₂O/t nitric acid and high pressure plants emit 9kg N₂O/t nitric acid (Ecofys 2009). Since the N₂O emissions depend on the features of each processed used and different technologies already implemented, the same country with different nitric acid plants have different rates of N₂O emissions. For example, in Norway there are medium pressure plants releasing 6-7,5 N₂O/t nitric acid, atmospheric pressure plants releasing 4-5 N₂O/t nitric acid and plants with Process-integrated N₂O destruction releasing less than 2 kg N₂O/t nitric acid. In the US nitric acid plants with NSCR (Nonselective Catalytic Reduction) release less than 2 kg N₂O/t nitric acid and plants without NSCR release 9,5 kg N₂O/t nitric acid. In other countries, nitric acid plants operating at dual pressure and with European design release 8-10 N₂O/t nitric acid and older plants (pre-1975), without NSRC release 10-19 kg N₂O/t nitric acid (IPCC 2000). An average European plant emits 6 Kg N₂O/t nitric acid corresponding to about 2 tons of CO₂ equivalent/t nitric acid; for existing plants with application of N₂O abatement technologies, N₂O emissions are 0,12-1,85 Kg N₂O/t nitric acid and for new plants (which are mostly medium/high dual pressure type plants) the N₂O emissions are 0,12-0,6 Kg N₂O/t nitric acid (BREF 2007). According to EFMA benchmarking survey about N₂O emissions from nitric acid plants reports that the average emissions of nitric acid plants is 6,1 Kg N₂O/t nitric acid and that BAT emission level ranges from 1,85 to 2,5 Kg N₂O/t nitric acid. NSRC technology has been developed for NO_x removal and has shown to be capable of reducing N₂O as well showing efficiencies of 70% but requiring the burning of extra fuel. EFMA(2000) and Ecofys (2009) do not

recognize NSRC as BAT technology for N₂O abatement potential. This will be discussed in a larger extended later on this report.

5 Methodology

In this chapter a narrative of the methodology used for this researched is presented. It starts by describing the type of model that it was created according to the goals initially determined. Afterwards it goes in detail about the type of methodology used in the calculations. It refers the advantages and disadvantages of using this approach. In the end of this chapter the system boundaries of the model are defined. They include the time frame the model is set to; it summarizes the technological options chosen for it; it specifies the type of GHG studied in the model and it characterizes the countries chosen for this survey in terms of its production.

5.1 The model

The scope of this research is to construct a computer model able to generate energy and CO₂ cost-supply curves for nitrogen industry. Making use of Microsoft Excel facilities, specific variables are defined and data is imputed; for instance, energy prices, energy consumption, discount rates, costs of technologies. After aggregating them, defining certain assumptions and executing the required calculations the model is able to simulate energy and CO₂ cost-supply curves.

This type of model fits in the so called bottom-up models or engineering economic. It is an approach rooted in engineering principles that account for physical flows of energy capital equipment. Bottom-up models start with disaggregated data and aggregated it to their own limits or goals (Mapping the energy future - IEA 1998). They provide detailed descriptions of energy technology systems: information on investment, capital stock turnover, operating and maintenance costs, life time of technical equipment, specified fuel use, efficiency data; and then aggregate it and driving it to some extent by assumptions about their implementation and efficiency; indicating in the end the potential for lowering energy use and associated CO₂ emissions depicted in the curves. In this case cost supply curves determine the energy savings potential and CO₂ emissions reductions potential in ammonia industry in 2030.

A drawback of this model is the fact that it is not accounting for non-physical variables that could influence the results. For instance, it is not accounted that the financial savings from energy efficiency improvements could have an economic feedback or rebound effect that raises demand for energy services by an amount dependent on the size of the income elasticity.

Previously referred, this model is integrating a certain number of assumptions. These assumptions are included in a number of variables such as production growth, existing capacity, structural changes, technological applicability and availability, stock turnover, etc. This impairs a degree of uncertain, crucial for the final results of the model.

5.2 Cost supply curves

Cost supply curves (or Conservation supply curves -CSC-) are designed to describe and compare the different energy conservation options in a simple way. They depict the quantity of conserved energy and the costs related to specific saving options showing also which ones are to be cost-effective. When CSCs depict distinct options for abatement greenhouse gas emissions potentials and its costs they are also called marginal abatement cost curves (MACC). The methodology is the same, except that the cumulated energy savings are replaced by cumulated greenhouse gas emissions abatement. In this research cost supply curves will be built according to the cost of conserved energy (CCE) and according to the specific CO₂ mitigation cost (CCO₂). Both costs are calculated from the sum of annualized investment costs plus the annual operating and maintenance costs minus the annual financial savings of the specific saving options divided by the annual energy savings or annual amount of avoided CO₂ emissions. The equations translating it are the following:

$$CCE = \frac{\text{Annualized Investment Cost} + \text{Annual O\&M costs} - \text{Financial Benefits from Saving Energy}}{\text{Annual Energy Savings}}$$

$$C_{spec}CO_2 - eq = \frac{\text{Annualized Investment Cost} + \text{Annual O\&M costs} - \text{Financial Benefits from Saving Energy}}{\text{Annual Amount of } CO_2 - eq \text{ emissions savings}}$$

The annualized investment cost is a function of the discount rate and life time of the technology. It is calculated according to the equation:

$$\text{Annualized Investment Cost} = \text{Investment Cost} \times \frac{d}{(1 - (1 + d)^{-L})}$$

D is the discount rate and L is the life time.

Thus, for each energy efficient measure, the conservation or the abatement potential and the correspondent specific cost are assessed and in the overall the measures are ranked according to their cost. Each measure is then plotted in a graph. On the Y axis is represented the cost of each conservation measure and on the X axis is represented the potential saving of each conservation measure or GHG emissions avoided. The curve shape looks like a ladder, where each step corresponds to one conservation measure. The conservation measures are ranked from the cheapest to the most expensive.

To calculate the annualized investment costs it was required to define a discount rate and a life time period. Technical life time depends on the characteristics of the equipment. Discount rate is meant to reflect the (risk) preference of the consumers/investors or society when evaluating (energy efficiency) investments (Worrell 2004). It ranges from low discount rates (4% to 8%) also called social discount rates to high discount rates matching the hurdle rates (Worrell 2004). The European Council for an Energy Efficient Economy (ECEEE) (2009) suggests that relatively high discount rates are more realistic in the case of industry. High discount rates are translated in pay back times (expectation) lower than 2 years on average and implicitly incorporating transaction costs; this translates the usual high ambition of industry investors. Howard & Sanstad defend that high discount rates reflect a rational evaluation of risk associated with an investment and efficient markets (Worrell 2004). In this research the discount rate was chosen to be 30%. This subject will be further addressed in chapter 10 - sensitivity analysis.

The CSC methodology has the advantage of showing graphically the technological options available, the costs of each of them and the potential energy savings or the CO₂ emissions avoided. CSCs are playing a major role in energy models for climate policy decisions makers (ECEEE 2009). However, it implies several drawbacks: CSC methodology do not include technological options that might be available in the long term and thus cannot be characterized; and although they include investment, operation and maintenance costs and financial benefits of energy savings, CSCs do not include the opportunity and the transaction costs for assessing the investment; CSCs deals with fixed/instantaneous energy prices that vary per region (that is accounted) but they are also determined by the season, by the structure of the market, by the energy provider, the quantity bought and the energy taxes; it does not account for the fact that large companies might be able to negotiate cost reductions in technologies and energy prices due larger orders; plus the saving potential of each technology depends strongly on the specific technological characteristics of the company; in addition, it is also uncertain how fast companies replace their technology, some might be faster than others because some companies might prefer to repair and retrofit several times before replacing; the rebound effect, that describes the increase in energy consumption as a direct consequence of cost savings due to energy conservation, is also not accounted in this methodology. Some of these examples reflect the fact that the "technological world" is heterogeneous but this methodology is treating it as an "average world". Several attempts to improve this methodology are in progress (ECEEE 2009).

5.3 System boundaries

5.3.1 Time frame

This research aims to study how technology in nitrogen fertilizer industry is going to evolve up to 2030. It has been proven that in the past years the technological development has already contributed to a decline in terms of energy consumption and CO₂ emissions. For example, the ammonia production started in 1956 and since then the energy consumption has been reduced by 30% (IEA 2007). Thus, this research proposes

is estimate how much energy can be saved and how many tonnes of CO₂ emissions can be avoided up to 2030.

5.3.2 Technology measures

Different technology measures have been identified on the ammonia, urea and nitric acid production process. Measures that are currently not available (Beer 1998) or are in a first stage of production are not included. For instance, IEA predicts that carbon capture and storage (CCS) measure for ammonia production process can only be implemented in 2050 (IEA 2006) therefore it was not included in this research. The technology measures chosen are commercially available today or will be in the near future. Investment costs, energy and emissions saving potential and current availability of the technologies were major criterias contributing for the decision making. The chosen measures decline the energy consumption and CO₂ emissions levels to the levels performed by best available techniques. They are a mix of retrofit measures (measures in which the equipment is upgraded) and revamping measures (measure in which the equipment is replaced by new one).

The proposed measures for ammonia production are described and aggregated, by each section of the overall process, on Rafiqul et al (2005). There are several other articles describing examples of best available techniques to reach low levels of energy consumption and CO₂ emissions reduction for ammonia production but they do not include the investment costs or specific energy savings per tonne of ammonia produced, essential criteria's for this research. Literature examples are: BREF – Ammonia (2006), EFMA – Ammonia (2000), UNEP – Ammonia (1998), Syngas Production from Coal (ETSAP 2010), Appendix B of EERE (2005).

One technology measure was selected for urea fertilizer and it is recommended by ECN (2009). There was a large quantity of literature describing other potential technologies but not referring the costs involved in the process just like in the case of ammonia measures. Examples are: BREF - Urea (2006), EFMA – Urea (2000), UNEP – Urea (1998).

Regarding the nitric acid technologies measures, the amount of literature available describing the best available techniques for nitric acid that do not include investment costs was even larger: BREF – Nitric Acid (2006), EFMA – Nitric Acid (2000), UNEP – Nitric Acid (1998), Methodology for the free allocation of emission allowances in the EU ETS post 2012 (Ecofys 2009), Good practice guidance and uncertainty management in national Greenhouse gas inventories (IPPC Guidelines 2000); Formation and control of N₂O in nitric acid production: where do we stand by today?(Ramírez et al 2003); Available and emerging technologies for reducing greenhouse gas emissions from the nitric acid production industry (EPA 2010). In the end the technologies proposed were found in an EPA report in 2004: Global mitigation of Non-CO₂ greenhouse gases.

The different technologies proposed for each fertilizer are presented in table 5.1:

	Technologies
Ammonia	Coal Gasifier Reformer
	Natural Gas steam reforming
	CO ₂ removal
	Synthesis
	Controls
	Process Integration
Urea	Pervaporation
Nitric acid	High Temperature Catalytic
	Reduction Method

Table 5.1: List of technologies proposed in this research.

The technologies proposed for ammonia are gathered per sector. As previously described, depending on the type of fuel used in each country different technologies are implemented. Natural gas is used on the steam reforming process and coal is used on the coal gasification process. There was no investment cost data found on oil based technologies. Apart from the reformer section, the following sections of the process are similar. The technologies are not competing between each other. The measures presented are assumed to remain constant over the period of the survey, 2005 to 2030. Technological learning effect is not included. More information about technology measures is presented in the next chapter.

5.3.3 GHG emissions

The main pollutant of the nitrogen fertilizer sector is the CO₂ released during the ammonia process. The high amount of CO₂ released is due to the chemical reaction that produces ammonia and originates CO₂ as a by-product; in less extent, there is also CO₂ release due to the burning of fuel used to supply heat in the reformer, for the auxiliary boiler. The electricity used is not significant. EFMA (2009) states that on average 70% of the CO₂ results from its use for feedstock and 30% from heating the feedstock.

The CO₂ emissions generated on the urea's production process are much less significant compared with than CO₂ emissions generated on the production process of ammonia. The calculations concerning CO₂ emissions due to urea are based on the energy consumption spent in the production process and on the fuel share of each country.

The production of nitric acid generates N₂O emissions that are harmful for the environment. In this report these emissions are calculated in terms of CO₂ emissions equivalent enabling the sum of the total CO₂ equivalent emissions released by the three fertilizers in study.

5.3.4 Geographical coverage

For this research, the data regarding fertilizer production, energy consumption intensity, CO₂ intensity and technological status was collected on a country level. There are 15 countries selected that account for 81% of the total ammonia production for the year of 2007 (USGV 2009). These same countries were chosen for urea and nitric acid survey, although for some countries its production is not representative (Table 5.2).

	Ammonia production (Mt)	Share in ammonia production (%)	Urea production (Mt)	Share in urea production (%)	CO ₂ emissions due to Nitric acid production (Mt CO ₂ -eq)	Share in CO ₂ emissions due to Nitric acid production (%)
Canada	4,401	3,50	4,864	4,53	1,260	1,91
China	53,998	42,89	44,856	41,77	21,440	32,50
Egypt	2,038	1,62	3,529	3,29	0,210	0,32
Germany	3,025	2,40	0,450	0,42	11,067	16,78
India	11,838	9,40	20,529	19,12	2,140	3,24
Indonesia	7,298	5,80	7,286	6,79	0,000	0,00
Iran	1,281	1,02	0,849	0,79	0,000	0,00
Netherlands	2,399	1,91	0,503	0,47	5,673	8,60
Pakistan	2,594	2,06	4,878	4,54	0,000	0,00
Poland	2,473	1,96	0,413	0,38	4,452	6,75
Russian F	12,276	9,75	5,535	5,15	3,193	4,84
Saudi Arabia	2,607	2,07	3,270	3,05	0,000	0,00
Trinidad	5,044	4,01	0,348	0,32	0,000	0,00
Ukraine	4,836	3,84	3,340	3,11	0,719	1,09
United States	9,800	7,78	6,726	6,26	15,810	23,97

Table 5.2: Nitrogen production and share of production in terms of total production in 2005.

5.3.5 Excluded processes

This report include all the processes of production ammonia, urea, and nitric acid described previously in terms of the energy consumption and CO₂ emissions; but it does not include the energy consumption and

CO₂ emissions to bring the raw materials to the plants, the energy required for the waste water treatment of certain by-products, and the energy required for the packaging and the transportation of the products.

6 Technology measures

This chapter gives an overview of the technologies that can be currently implemented on the nitrogen fertilizer industry. The information, provided in the next paragraphs, includes a description of the measures, a summary of energy savings, the lifetime of the technologies, the costs of the correspondent measures and the procedure used to calculate the CO₂ emissions avoided by the measures suggested.

6.1 Ammonia's technology measures

The energy reduction measures chosen for ammonia on this research were based on two main articles: Bartels et al (2008), Rafiqul et al (2003). A data sum was gathered and is showed on tables.6.1, 6.2, 6.3. An explanation of each measure is presented in the next paragraphs.

The ammonia production process depends on a first stage on the type of fuel used: natural gas, coal or oil. The main differences regarding the fuel used happen in the reforming section. Therefore two technologies chosen for the same section: coal gasification – reforming section and steam reforming process – reforming section. No data was found for gasification process based on oil. The coal gasification is suggested by Bartels et al (2008). The authors collected eight choices for implementing new coal gasification systems based on four different articles; the data provided is listed by ammonia size plant, total capital costs and if it incorporates sequestration of CO₂ or not. The cheapest coal gasification option that did not include sequestration was chosen (Weinheim, 1999). The energy savings for this technology were calculated based on the difference between the specific energy consumption of a coal based ammonia plant in China in 2005 (Table 6 Zhou et al 2010) and the BAT specific energy consumption for new plants based on coal (Annex.1 IFA 2009). According to Rafiqul et al (2003), an average ammonia plant consumes 58% of its energy on the reforming section, thus, to be more accurate, the previous calculation also accounts for this detail. Coal gasification – reforming section is only applied in China due to its large use of coal as a fuel and feedstock in the ammonia production process (Zhou et al 2010). The final results are presented in table 6.1 – coal gasification – reforming section.

Apart from the reforming section, the other steps in the ammonia production process are relatively similar. Technology measures were selected for the carbon dioxide recovered section, ammonia synthesis and separation, machinery and process automation, and process integration. For the shift section, Rafiqul et al (2003), recommends the use of new types of high-pressure shift catalysis; for the final purification of synthesis gases it is recommend the use of pressure swing absorption; but for both of this sections the costs are not quantified. In the case of the abatement technologies for ammonia synthesis, it is unclear if the costs and savings include the recovery of ammonia and hydrogen from the purge gas. According to Caddet (1998) these savings can represent 0,002 GJ/t NH₃ and according to Beer et al 1994 in ICARUS-3 hydrogen recovery can generate savings of 0,8 GJ/t NH₃ for 10 € /GJ saved. Machinery and process automation and process integration are not part of the stages of producing ammonia but its performance is quite important in the overall process; there is great potential savings particularly in the case of process integration (table 6.2). There was also other source mentioning costs regarding abatement technologies for ammonia process: ICARUS-4 Nieuwlaar 2001. The data from this source was not used because what was reported was not as global, complete and detailed as Rafiqul et al (2003). However it is still quite relevant in the ammonia abatement technologies field thus these data is included on table 6.3 as a reference.

Suggestions of Technologies opportunities	Energy savings GJ/t	Investment costs €/GJ	O&M €/GJ	Life time yrs	References
<i>Coal gasification – Reforming section:</i>	6	708	4%	20	Weinheim, 1999

Table 6.1: Technology proposed by Bartels et al (2008).

Suggestions of Technologies opportunities	Energy savings GJ/t	Investment costs €/GJ	O&M €/GJ	Life time yrs	References
<i>Steam Reforming process - Reforming section:</i> Installation of a pre reformer Installation of a gas turbine Reduction of the flue gas temperature Avoid heat loss by proper insulation of the reformer furnace Increase of pre-heat temperatures for feed, steam and air used in the process Increasing operating pressure Lower steam-carbon ratio Shifting of partial reformer duty from primary to secondary reformer, using excess air or oxygen -enriched air in the secondary reformer Overall:	4	65		20	De Beer, 1998 + Hendricks C. et al, EU 2001
<i>Carbon dioxide recovered section:</i> Use of advanced solvents Pressure swing absorption or membranes Overall:	1	15		20	BREF 1997 + Hendricks C. et al, EU 2001
<i>Ammonia synthesis and separation:</i> Lower ammonia synthesis pressure Improved catalysis Adjustments in the power system and in the recycled loop Overall:	1,5	25	1	20	UNEP 1998 + Hendricks C. et al, EU 2001
<i>Machinery and process automation</i> Process automation	0.6	10		20	UNEP 1998
<i>Process integration</i> Use of better process integration of heat exchange reformers and co-generation of heat and power	3,5	10		20	De Beer et al, 1994 - ICARUS-3

Table 6.2: Technologies proposed by Rafiqul et al (2003).

Suggestions of Technologies opportunities (Ammonia)	Energy savings GJ/t	Investment costs €/GJ	O&M €/GJ	Life time yrs	References
<i>Steam Reforming process - Reforming section:</i> (page66) Installation of a Pre reformer (retrofit) 4%*32,2= Auxiliary steam generation (retrofit) 2,5%*32,2= Overall:	1,3 0,8 2,1	7,25 45 52,5	0,25 1,5 1,75	25 25	IDEE 2001; Huurdean 2001; ICARUS-4 ICARUS-4
<i>Carbon dioxide recovered section:</i> Improved solvents for CO ₂ removal	1,4	3	0	25	ICARUS-4 (ex: HydroAgri Plant)
Hydrogen recovery (retrofit)(page 67)	0,8	10	0,25	25	Beer et al 1994 - ICARUS-3
<i>Process integration (retrofit)(page 68)</i> 0,04%*32,2=	1,3	15	0,5	25	ICARUS-3

Table 6.3: Technologies proposed by (ICARUS-4 Nieuwlaar 2001)

The amount of avoided CO₂ emissions, correspondent to the previous technologies chosen, was calculated by multiplying the amount of energy saved times the emission factor and according for the fuel share used in each country. More information is presented in chapter 8.

6.2 Urea's technology measures

The technology measure chosen for urea was based on EERE(2005) and on ECN(2009). EERE(2005) mentions that energy can be saved implementing pervaporation technology (hybrid technologies involving membranes and distillation). In the US, urea production reached 3260kt N in 2005. ECN (2009) confirms it stating that it is technically easier and economical more interesting to replace distillation with hybrid systems than to totally replace it with an alternative technology. Hence, data from EERE(2005) regarding the energy savings (2 PJ) and urea production of the United States (3260kt N) was used as a reference together with data concerning urea production of the Netherlands (480kt N) to calculate the potential energy savings of this technology. The results show that this technology can save 0,3PJ ((2PJ*480kt N)/3260 kt N or 0,31 GJ/t urea) on Dutch urea production plants per year. ECN(2009) estimates that the investment cost of pervaporation is 15 €/GJ*a with an additional O&M cost at 0,3 €/GJ.

Suggestions of Technologies opportunities (Urea)	Energy savings GJ/t	Investment costs €/GJ	O&M €/GJ	Life time yrs	Reference
Pervaporation	0,31	15	0,3	25	EERE 2005 + ECN 2009 (page 30)

Table 6.4: Technology measure of urea.

ICARUS-4 2001 (pages 22 and 69) highlights the fact that according to Beer et al (1994) the energy use of modern urea plants may be as low as 2.75 GJ/t Urea; according to Worrell et al (1992), the energy use in Dutch Urea plants is estimated at 3.05 GJ/t Urea. Thus, an energy efficiency improvement of 11% is deemed achievable. This would entail a specific investment cost of €25/GJ. However, no technologies were suggested about how to reach this energy efficiency improvement so this information was not used in this research, leaving pervaporation measure as the only technology reliable as abatement technology for urea production.

The correspondent CO₂ emissions avoided due to the energy saving measure proposed for urea plants were calculated multiplying the amount of energy saved by the emission factor, accounting for the fuel share mix used in each country.

6.3 Nitric acid's technology measures

Emissions of nitric acid plants vary substantially depending on operating pressures, catalysis, concentration of nitric acid and abatement processes (Ecofys 2009). However, Ramírez et al 2003 states that N₂O emissions depend exclusively on the ammonia combustion process: once N₂O is formed it passes unreacted through the plant, not being affected by the operating condition in the absorber or eventual NO_x abatement technology like SCR after treatment in the tail gases.

Compare the performance of all the plants is not straightforward and specific abatement techniques cannot be applied homogeneously in all the plants. Still, several emission abatement techniques are commercial available and under further development and testing (Ecofys 2009). Ecofys 2009 proposes gathering this technologies in three groups corresponding to three different stages in the nitric acid production or tail gas treatment: primary (suppression of N₂O formation); secondary (removal of N₂O in the burner after the ammonia oxidation gauzes by homogeneous decomposition or using high temperature catalytic reduction method; tertiary (removal of N₂O from the tail gas using the non-selective catalytic reduction method (NSRC) or the selective catalytic reduction). Ramírez et al 2003 proposes

gathering the measures in 4 different groups according to the position in the process: primary abatement measures aim to avoid N₂O to be formed changing the ammonia oxidation process and/or catalysis; the secondary abatement measures aim to remove N₂O from the NO_x gases between the ammonia converter and the absorption column; the tertiary abatement measures are applied in the tail gas leaving the absorption column destroying the N₂O; the quaternary abatement measures are applied at the pure end of the pipe solution. Table 11 and figure 16 of Ramir ez et al (2003) present the techniques involved in each stage and the cost-efficiency of each measure in the case of new and existing plants. Although this article is quite detailed in data concerning the quantity of N₂O emissions released and abatement technologies, it lacks in presenting it on a company applicability perspective. Moreover, the data cost exhibited was not used as a reference in this research because prices were presented in terms of cost-efficiency ( /t CO₂-eq produced) and not in terms of cost-effectiveness ( /t CO₂-eq saved).

US EPA 2006 gathers N₂O abatement option opportunities for nitric acid plants in 3 groups: high-temperature catalytic reduction method (this abatement option has several variations developed by different companies all involving the decomposition of N₂O into nitrogen and oxygen using various catalysis - 90% efficiency); low-temperature catalytic reduction method (this one is similar to the previous one except that it does not require heat to decompose the N₂O; propane needs to be added to the gas stream - 95% efficiency) and nonselective catalytic reduction (NSCR) (it converts the nitrogen oxides to elemental nitrogen using extra fuel and a catalyst to consume the free oxygen in the tail gas; the additional fuel emits CO₂. In table 1-5 of the same article, total costs, O&M costs and lifetime of reducing N₂O emissions from industrial processes are presented for each company and for each abatement technology. Most companies are implementing the high temperature catalytic reduction method: Grand Paroisse, BASF, Norsk Hydro and HITK. Ecofys 2009 confirms this information adding that companies like Heraeus, Johnson Mathew, Umicore and Yara are also implementing this technology. The second technology (low-temperature catalytic reduction) is being implemented by Krupp Uhde EnviNox. EFMA (2009) affirms that this technology is well-tested and proven operating at high temperatures but it is only practical for use at tail gas temperatures above 400 C and economically compatible for large nitric acid plants (>40000 metric t/year). Therefore the level of implementing this technology is very limited to a few numbers of nitric acid plants and for that reason it was not integrated in this research. The third technology (NSRC) requires considerable energy consumption and leads to significant methane emissions in addition to CO₂ and ammonia to air. Both, BREF 2007 and EFMA 2009, exclude it as a BAT for N₂O emissions reduction in nitric acid plants. Thus NSRC was also not included in this report.

In the overall scope only one technology was chosen: High temperature catalytic reduction method (the prices were averaged).

Suggestions of Technologies opportunities (Nitric Acid)	Reduction efficiency %	Investment costs �/t CO ₂ eq	O&M �/t CO ₂ eq	Life time yrs	Reference
High temperature catalytic reduction method	90	2,25	0,14	10	US EPA 2006

Table 6.5: Technology measure of nitric acid.

7 Technology assumptions

The model required the implementation of several technical assumptions. In this chapter, the technological assumptions and the sources of these technological assumptions are mentioned on a country basis. They include the nitrogen production, the specific energy consumptions, the fuel mix, the fuel prices, the investment costs differences used for each country and the explanation of the capital stock turnover applied in this research.

7.1 Nitrogen production data

On a first stage the biggest producers of ammonia were selected from a U.S. Geological Survey report (2009) in the year of 2007 (in thousand metric tons of nitrogen). On a second stage the ammonia production data (in tonnes of ammonia) for 2007 was collected for the 10 biggest productive countries from YARA (2008) report and updated to the reference year (2005) using IFA Production and International Trade Production and Trade Statistics. For the less productive countries (Egypt, Iran, The Netherlands, Pakistan and Poland) YARA did not provided information so data was collected from Worldwide Ammonia Capacity Listing by Plant - IFDC 2008 for the year 2005.

The case of Urea is analogous. Urea production (tonnes of urea) data was collected from YARA 2008 regarding the year 2007 (10 biggest productive countries); for the less productive countries (Germany, Iran, The Netherlands, Poland and Trinidad and Tobago) data was collected for the year 2002 from Nitrogen - USGV 2004; using the IFA Production and International Trade Production and Trade Statistics the rate for the year production of 2005 was calculated.

As it mention previously, in the case of nitric acid, it was not possible to collect the amount of nitric acid produced in the majority of the countries. Instead, total N₂O emissions from the nitric acid plants were gathered. In most countries (Canada, Germany, The Netherlands, Poland, Russia, Ukraine, United States) data was collected from UNFCCC – National non- CO₂ Greenhouse gases reports and in other cases (China, Egypt, India) from Global Anthropogenic Emissions of Non-CO₂ Greenhouse Gases 1990-2020 (EPA Report 430-R-06-003) Appendix spread sheets. In this report a fix rate of the N₂O emissions from adipic acid and nitric acid plants is applied as an assumption (33% and 66% respectively). Data refers to the year of 2005. The rest of the countries (Indonesia, Iran, Pakistan, Saudi Arabia and Trinidad and Tobago) do not have nitric acid plants, thus they do not release N₂O emissions.

Assumptions regarding the production data for the year of 2030 were made; they are described in chapter 8.

7.2 Specific energy consumption data

Due to lack of data regarding energy intensity consumption per process for each country, data was collected in terms of energy intensity consumption overall process of each country. Specific energy consumption data for ammonia and urea production per country is presented in table 7.1.

	SEC (GJ/t NH ₃)	Reference	SEC (GJ/t Urea)	Reference
Canada	34,4	Benchmarking energy efficiency and carbon dioxide emissions - CFI 2008	3,78	Assumption based on "Average NL technology 2002" Lako et al - ECN 2009
China	51,32	The Chemical Fertilizer Industry in China - IFA 2009	4,67	Assumption based on "European Technology Old" Lako et al - ECN 2009
Egypt	39	Own estimation based	4,67	Assumption based on

		on conversation with Prof. Worrell		“European Technology Old” Lako et al - ECN 2009
Germany	37,3	CPS–OECD/IEA 2009	3,78	Assumption based on “Average NL technology 2002” Lako et al - ECN 2009
India	40,2	CPS–OECD/IEA 2009	4,67	Assumption based on “European Technology Old” Lako et al - ECN 2009
Indonesia	39,9	Natural gas and nitrogen fertilizer production in Indonesia - IFA 2007	4,20	Assumption based on “European Technology Average” Lako et al - ECN 2009
Iran	37	Own estimation based on conversation with Prof. Worrell	4,67	Assumption based on “European Technology Old” Lako et al - ECN 2009
Netherlands	31	Lako et al - ECN 2009	3,78	“Average NL technology 2002” Lako et al - ECN 2009
Pakistan	38,5	Own estimation based on conversation with Prof. Worrell	4,67	Assumption based on “European Technology Old” Lako et al - ECN 2009
Poland	39	Own estimation based on conversation with Prof. Worrell	4,20	Assumption based on “European Technology Average” Lako et al - ECN 2009
Russian F	40	“Benchmarking energy efficiency and carbon dioxide emissions” (CFI 2008)	4,20	Assumption based on “European Technology Average” Lako et al - ECN 2009
Saudi Arabia	36	CPS–OECD/IEA 2009	3,78	Assumption based on “Average NL technology 2002” Lako et al - ECN 2009
Trinidad e Tobago	36,9	Saygin, D. estimation	3,78	Assumption based on “Average NL technology 2002” Lako et al - ECN 2009
Ukraine	39	Own estimation based on conversation with Prof. Worrell	4,20	Assumption based on “European Technology Average” Lako et al - ECN 2009
United States	38	CPS–OECD/IEA 2009	4,20	Assumption based on “European Technology Average” Lako et al - ECN 2009

Table 7.1: SEC of ammonia and urea per country.

7.3 Fuel mix

According to the literature most countries use natural gas in their ammonia plants (CPS–OECD/IEA 2009). Exceptions are for China (using 78% of coal and 22% of natural gas) and India (using 70% of natural gas and 30% of oil) in the year of 2006 (CPS–OECD/IEA 2009).

7.4 Fuel prices

For this model, different sources were collected for fuel prices. The natural gas prices collect were from American Chemical Society Slides 2005; the prices for coal and the oil were collected from International Energy Agency (IEA 2007). Prices regarding electricity were not accounted because, although, ammonia production process requires electricity, its amount is insignificant in the overall process. Table 7.2 shows the fuel prices used in the model:

	Natural Gas (€/GJ)	Coal (€/GJ)	Oil (€/GJ)
Canada	6,360		
China	3,739	0,651	
Egypt	0,617		
Germany	4,356		
India	2,506		6,149
Indonesia	2,082		
Iran	0,964		
Netherlands	4,356		
Pakistan	2,506		
Poland	2,621		
Russian F	0,925		
Saudi Arabia	0,578		
Trinidad	1,234		
Ukraine	1,619		
United States	7,478		

Table 7.2: Fuel prices (2005).

Euro exchange: 0,813361 (for August 2005)

7.5 Investment costs difference

The data collected regarding the investment costs and the operation and maintenance costs for the different technologies was not found on a country level. However, due to differences at economic level and natural resources availability, the costs involved in manufacturing and implementing the same technologies are expected to vary from country to country. In order to reproduce this heterogeneity, believed to be more closed to reality, it was incorporated an extra detail from an IEA report: "Uncertainties in relation to CO₂ capture and sequestration"(Gielen 2003). In this report it is presented a table (table 7.3) that aims to disaggregate the investment costs and operation and maintenance costs according to different regions. The author justifies it mentioning that there might be differences on the exchange rates (for instance the exchange rates for developing countries can fluctuate from a factor of 2); on the system boundaries of the project (for example in developing countries might be required to build up new infrastructures); on the cost factor (in some countries it is necessary to import the technologies while in other they can be produced locally); on the skilled labour available (this is a limiting factor in developing countries); on the labour wages (in developing countries are much lower)(Gielen 2003). Accounting for all the factors mentioned, region cost multipliers were developed and applied, covering 15 regions. The reference database country chosen was the United States. The original table presented by Gielen 2003 (table 7.3) and the adapted table (table 7.4) used in the model are showed below:

Country/Region	INVCOST	O&M
Africa	1,25	0,9
Australia	1,25	0,9
Canada	1	1
China	0,9	0,8
Central and South America	1,25	0,9
East Europe	1	0,9

Country	INVCOST	O&M
Canada	1	0,9
China	0,9	0,8
Egypt	1,25	0,9
Germany	1,1	1
India	0,9	0,8
Indonesia	1,25	0,8

Former Soviet Union	1,25	0,9
India	0,9	0,8
Japan	1,4	1
Middle East	1,25	0,9
Mexico	1	0,9
Other Developing Asia	1,25	0,9
South Korea	1	0,9
USA	1	1
West Europe	1,1	1

Table 7.3: Table from IEA report Gielen 2003.

Iran	1,25	0,9
Netherlands	1,1	1
Pakistan	1,25	0,8
Poland	1	0,9
Russian F	1,25	0,9
Saudi Arabia	1,25	0,9
Trinidad	1,25	0,8
Ukraine	1	0,9
United States	1	1

Table 7.4: Adapted table for end use in this research.

7.6 Capital stock turnover

The energy efficiency of the industry sector is dependent on stock turnover and on the retrofit of existing stock (Worrell 2005). Meaning that for a company to remain competitive the old equipment has to be regularly replaced by new equipment and/or additional technologies should be added to the old equipment. The lifetime and retirement of the old equipment are important to characterize stock turnover. Since it was not possible to acknowledge the age of the equipment for each country and how often the companies replace their equipment assumptions were made. In general terms, it was defined that for all the countries and for a specific future scenario the new plants build up to 2030 would operate at the best available techniques and the old plants would decrease their energy efficiency by a certain percentage per year during the next 25 years. These assumptions are characterized quantitatively and described in detail in the next chapter.

8 Baseline scenarios

A baseline scenario is any datum against which change is measured. It might be a current baseline, where observable and present-day conditions are represented; it might also be a future baseline, in which a projected future set of conditions excluding the driving factor of interest are characterised. Alternative interpretations of the reference conditions can give rise to multiple baselines (IPCC 2010).

In this report three scenarios are defined: a baseline/reference scenario (2005), a frozen efficient scenario (2030) and a business as usual scenario (2030).

In this context, the baseline scenario is usually defined according to population projections, economic development, energy use (energy intensity and carbon intensity) and land use change. The specific data gathered and the assumptions required are of critical importance for the construction of baseline scenario of the model. However, substantial uncertainty remains. In this case it is mainly due to uncertainty in GDP growth, population growth and fertilizers production growth.

For this report, based on the year of 2005, the financial crises of 2008/2009 is not accounted because it is believed that it will not have a major effect on the nitrogen sector up to 2030.

In the next paragraphs the baseline scenarios concerning the nitrogen production, energy consumption and CO₂ emissions of the nitrogen fertilizers are described.

8.1 *Baseline nitrogen production*

The database used for baseline production in 2005 was already mentioned in chapter 7.1 Nitrogen production – Technology assumptions. The baseline production in 2030 was defined equally for the frozen efficiency scenario and for the business as usual scenario. In this study the growth rate of the baseline production scenarios is based on an IEA scenario described on Energy Technology Transitions for Industry (ETTI – IEA 2009). The ammonia production projection for the year 2030 is presented in terms of the demand of consumption per capita. It was estimated on the basis of projected income per capita and historically derived relationships of the chemicals demand. It includes expected developments on the basis of implemented and planned energy and climate policies (ETTI – IEA 2009). The growth demand of consumption for ammonia production was assumed to equal the growth demand of production. The production of ammonia was calculated by first multiplying the consumption per capita by the population (Annex C ETTI – IEA 2009) and then calculate growth rate for production. In four countries (United States, The Netherlands, Germany and Canada) production growth rate was assumed to be zero. Until 2030 it was defined that these countries will not implement new plants. Results are showed in figure 8.1.

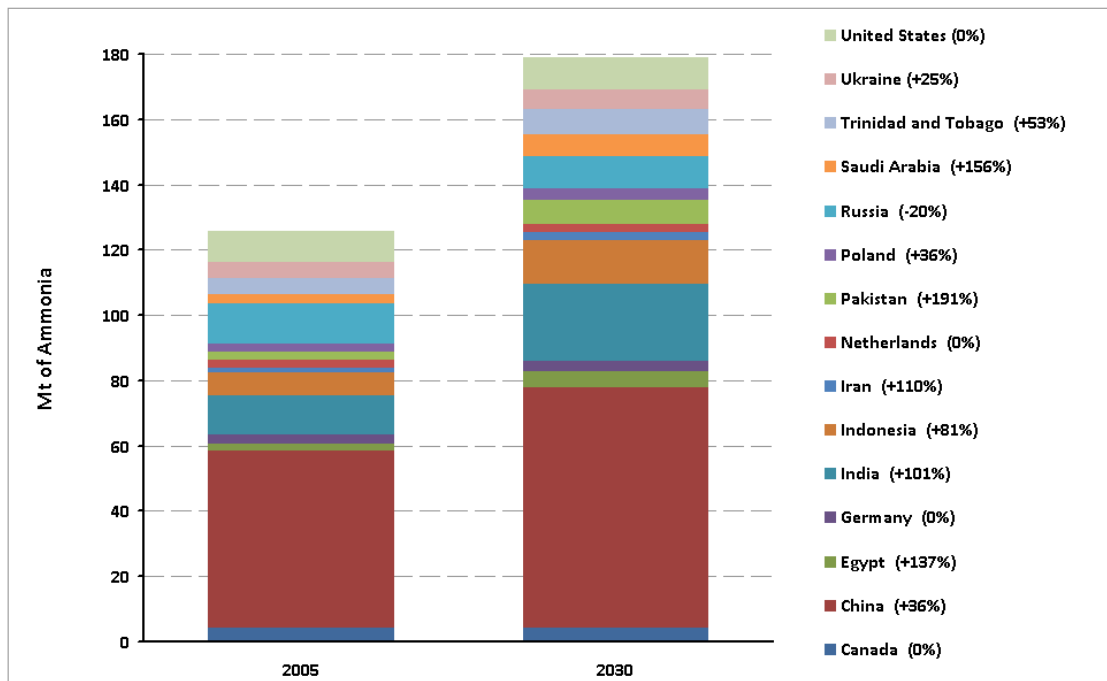


Figure 8.1: Ammonia production in 2005 and 2030.

It is relevant to mention that while most countries present a positive growth rate, Russia presents a negative growth rate facing a serious problem of expected decrease of the population in 2030. On the other hand, Pakistan shows the highest rate for production rate, due to an expected demographic explosion in 2030 (Raisson 2010).

It was assumed that urea and nitric acid behavior production growth will follow the same trend; in this sense the same methodology and the same assumptions were used to calculate the production growth rates for 2030 of urea and nitric acid.

8.2 Baseline energy consumption

On the previous chapter, Table 8.1 exhibits the specific energy consumption for reference scenario 2005. The baseline/reference scenario of energy consumption for 2005 and for the frozen efficiency scenario in 2030 was assumed to be the same. For the business as usual scenario the situation differs. This study was developed for ammonia and urea. Nitric acid was excluded because the process of producing nitric acid does not imply the consumption of energy; however it was included in the baseline scenario of CO₂ emissions. The following table presents the differences:

"Frozen efficiency"	"Business-as-usual"
<ul style="list-style-type: none"> • Energy intensity remains at 2005 levels; • No efficiency improvements; • New production remains at 2005 energy intensity levels; 	<ul style="list-style-type: none"> • Energy intensity decreases; • Energy consumption of old production drops by 0,15% per year; • Energy consumption of new production is operating at BAT levels; • For all ammonia new plants it is assumed that they operate at 27 GJ/t NH₃ (IFA 2009) except China and India due to differences in share of fuel; • BAT of energy consumption for urea is 3,20 GJ/t urea (IFA 2009); • It is assumed that nitric acid plants emit 95% less than current plants;

Table 8.1: Differences between Frozen efficiency and Business as usual scenarios.

The results of these assumptions are presented in chapter 9 (Results).

8.3 Baseline CO₂ emissions

The previous assumptions were used to define baseline scenario, the frozen efficiency and the business as usual scenarios for CO₂ emissions. For ammonia and urea, CO₂ emissions were calculated by multiplying the energy consumption data by the emission factor (Blok & Worrell 1994) accounting for the fuel mix of each country. Part of the CO₂ emissions produced in the ammonia process is used in the urea production. It was assumed that all urea produced used CO₂ released in the ammonia production (per each ton of urea produced 0,733 of CO₂ is consumed (IEA 2007)). The CO₂ emissions due to urea production and the CO₂ equivalent emissions due to nitric acid are added in the overall sum of CO₂ emissions. The emissions allocated to nitric acid are explained in sub-chapter 7.1. Figure 8.2 and table 8.2 present the amount of GHG emitted by each country for the baseline scenario in 2005.

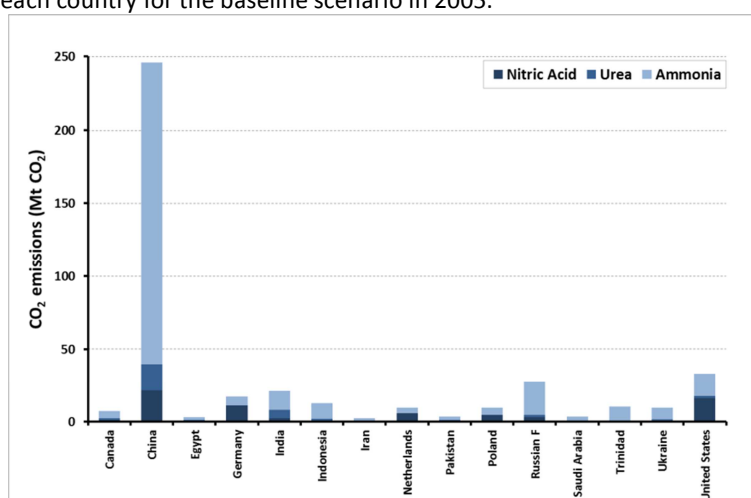


Figure 8.2: GHG emissions due to ammonia, urea and nitric acid processes in the 2005 baseline scenario.

Generated CO ₂ from Ammonia	Generated CO ₂ emissions per tonne of Ammonia produced	CO ₂ emissions due to Urea production	Consumption of CO ₂ due to Urea 2005	CO ₂ emissions due to Ammonia production	CO ₂ eq emissions due to Nitric Acid production	Total 2005
Mt CO ₂	t CO ₂ /t NH ₃	Mt CO ₂	Mt CO ₂	Mt CO ₂	Mt CO ₂	Mt CO _{2-eq}
8,48	1,93	1,03	3,57	4,91	1,26	7,20
239,49	4,44	18,06	32,88	206,61	21,44	246,11
4,45	2,18	0,92	2,59	1,86	0,21	2,99
6,32	2,09	0,10	0,33	5,99	11,07	17,15
27,73	2,34	5,96	15,05	12,68	2,14	20,78
16,31	2,23	1,71	5,34	10,97	0,00	12,68
2,65	2,07	0,22	0,62	2,03	0,00	2,25
4,17	1,74	0,11	0,37	3,80	5,67	9,58
5,59	2,16	1,27	3,58	2,02	0,00	3,29
5,40	2,18	0,10	0,30	5,10	4,45	9,65
27,50	2,24	1,30	4,06	23,44	3,19	27,94
5,26	2,02	0,69	2,40	2,86	0,00	3,55
10,42	2,07	0,08	0,26	10,17	0,00	10,25
10,56	2,18	0,79	2,45	8,11	0,72	9,62
20,85	2,13	1,58	4,93	15,92	15,81	33,32

China is certainly the large contributor of the GHG emissions in the nitrogen fertilizer sector. Its emissions represent 59% of the overall GHG emitted. United States is the second largest GHG emitter (representing 8% in the overall). The GHG emissions released by this country are mainly due to ammonia and nitric acid production, reaching almost 50% each. United States is also the second highest producer of nitric acid in the world and consequently the second highest emitter of N₂O. The third and the fourth major GHG

emitters are Russia and India (contributing 5% and 7% in the overall respectively). India is producing significantly more urea fertilizer than Russia; in which, according to the methodology used, is consequently consuming more CO₂ that is being subtracted in the overall amount of GHG emitted; if it would not be the case than Russia and India would swap places in the ranking.

9 Results

In this chapter the results regarding the energy and GHG emissions savings potential are presented. The study is covering 81% of the nitrogen fertilizer production and is including the three main nitrogen based fertilizers: ammonia, urea and nitric acid.

9.1 Energy consumption according to the baseline scenarios

As stated previously, baseline scenario for the reference year of 2005 and two future baseline scenarios were defined in this survey: the frozen efficiency scenario and the business as usual scenarios. Concerning energy consumption, only ammonia and urea data was gathered due to exportation of energy involved in the nitric acid production process.

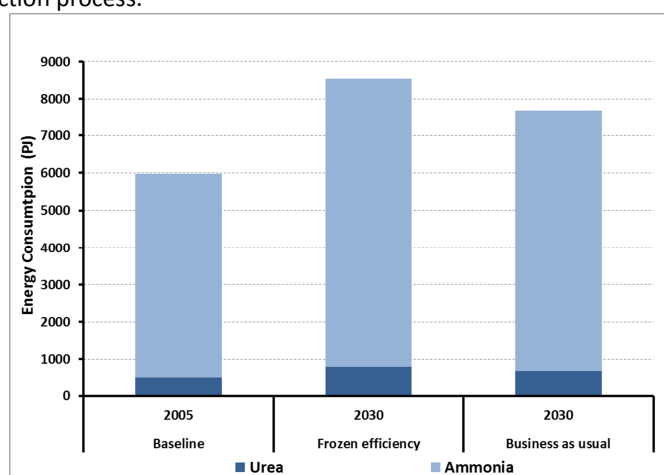


Figure 9.1: Energy consumption according to the baseline scenarios.

In 2005 the energy consumption is 6014 PJ, in which ammonia represents 92% of it (5532 PJ). According to the model, it is expected that from 2005 to 2030 energy consumption increases by 43% in the frozen efficiency scenario and by 28% in the business as usual scenario. More specifically, ammonia is expected to increase its production by 37% in the frozen efficiency scenario and 28% in the business as usual. On comparison, the energy consumption of urea is expected to increase its consumption by 29% in the frozen efficiency scenario and 28% in the business as usual scenario. As predicted the total energy consumption of the frozen efficiency scenario is higher than the total energy consumption of the business as usual (11%, 921 PJ). The country with the biggest impact on average per scenario is China (~50%), followed by India and Russia (~9%) and United States (~6%).

9.2 GHG emissions according to baseline scenarios

The results of the GHG emissions for the baseline scenarios are presented in this sub-chapter. For ammonia and urea the GHG emissions do not depend linearly on the energy consumption because they vary according to the different mix fuel share of each country (which differs in the case of China and India as mentioned). GHG emissions scenarios account for the GHG emissions of ammonia, urea and nitric acid production. Figure 9.2 exhibits the results.

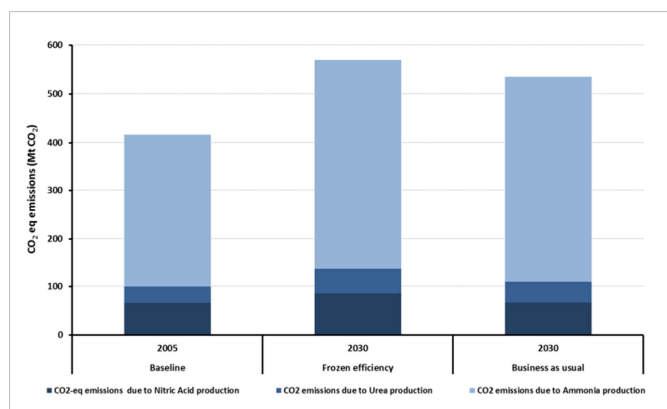


Figure 9.2: GHG emissions according to the baseline scenarios.

The GHG emissions released in 2005 due to nitrogen fertilizers reached 418 Mt CO₂. Ammonia is the fertilizer contributing the most for the global GHG emissions released by the nitrogen fertilizers industry. Its contribution is quite similar for each different scenario: 76% (318 Mt CO₂) in 2005, 77% (434 Mt CO₂) in the frozen efficiency scenario in 2030 and 78% in the business as usual scenario (377 Mt CO₂). GHG emissions released by nitric acid production are the second highest contributor; they range from 16% in the baseline scenario (66 Mt CO₂), decreasing to 14% in the frozen efficiency scenario (77 Mt CO₂) and dropping to 12% in the business as usual scenario (66 Mt CO₂). Urea fertilizer production process is the less polluter in terms of GHG emissions released, contributing 8% on baseline scenario in 2005 (34 Mt CO₂) and in the business as usual (52 Mt CO₂) and 9% in the frozen efficiency scenario (42 Mt CO₂). The total GHG emissions are expected to increase 26% from 2005 to 2030 in the frozen efficiency scenario (564 Mt CO₂ in FE), and 14% in the business as usual scenario (486 Mt CO₂ in BAU). The situation of the countries that have the biggest impact in terms of GHG emissions for ammonia and urea is similar as energy consumption mentioned previously. Regarding the nitric acid the situation is quite different because the biggest producers are China (32%), Germany (17%) and United States (24%).

9.3 Energy and emissions savings potentials in the baseline scenarios

In the next paragraphs the costs of the technologies and the energy and the GHG savings potential of the nitrogen fertilizer industry are presented. The calculations of it followed the methodology described in chapter 5. In the graphs depicted onwards the average cost of each technology will be shown in the Y axis and the cumulative energy savings or the cumulative GHG emissions avoided for each technology is shown in the X axis.

9.3.1 Energy savings potential of ammonia in the baseline scenarios

Figure 9.3 depicts the average cost of each five technologies that can be applied in the ammonia industry and the potential cumulative energy savings for the frozen efficiency and for the business as usual scenarios.

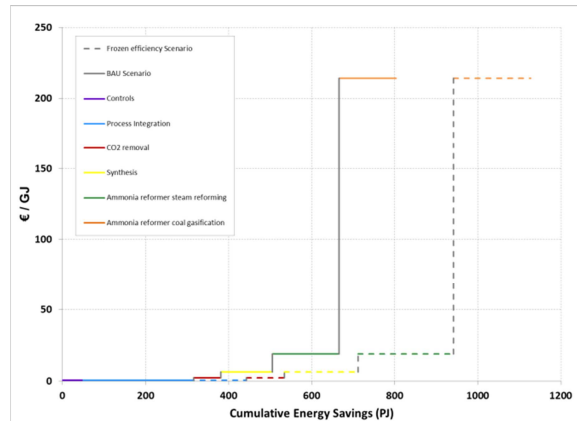


Figure 9.3: Overall energy savings potential of ammonia production for the frozen efficiency and business as usual scenarios.

	CCE (Discount rate 30%) (€/GJ)	Frozen efficiency Energy Savings 2030 (PJ)	BAU Energy savings (PJ)
Controls	0,562	70	49
Process Integration	0,562	372	260
CO2 removal	2,246	92	64
Synthesis	6,501	177	122
Ammonia reformer steam reforming	19,094	229	155
Ammonia reformer coal gasification	214,176	186	137
Total		1127	787

Table 9.1: Average costs of technologies and energy savings potential of ammonia fertilizer.

As expected, on global terms, the total energy savings potential of the frozen efficiency scenario (1127 PJ) is higher than the total energy savings potential of the business as usual (787 PJ) (Table 9.1). The savings regarding the BAU scenario are only applied to the production of 2005 because it is assumed that the new production of 2030 will be running on the BAT levels. The total savings of the frozen efficiency scenario represent 14% on the overall energy consumption of 2030 frozen efficiency scenario; the same calculation represents 11% on the business as usual scenario.

On average, none of the technologies regarding the ammonia fertilizer are cost-effective. However, the costs of the first and second technologies proposed, controls and process integration, are quite cheap. The correspondent savings accounted for process integration are considerably high: 372 PJ in the frozen efficiency and 260 PJ in the business as usual (Table 9.1), contrasting with the lower energy savings potential of controls technology, 70 PJ on the frozen efficiency scenario and 49 PJ on the business as usual scenario. Due to its high cost, the chances of implementing the coal gasification technology are very low.

9.3.2 GHG emissions savings of ammonia in the baseline scenarios

Figure 9.4 depicts the CO₂ emissions savings potentials for the different ammonia technologies. In the frozen efficiency scenario, CO₂ abatement potential technologies can save about 82 Mt CO₂, and in the business as usual they can potentially save 58 Mt CO₂ (Figure 9.4).

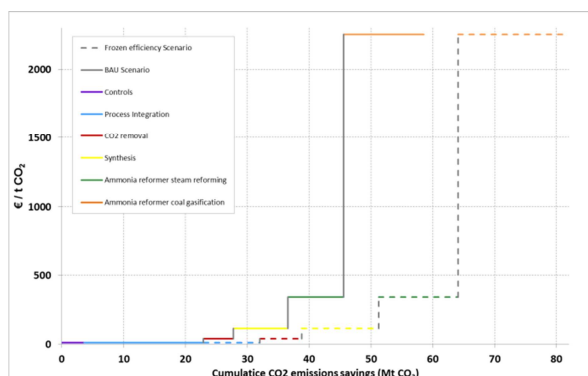


Figure 9.4: Overall CO₂ emissions savings of ammonia production for the frozen efficiency and business as usual scenarios.

	CCO ₂ (Discount rate 30%) (€/t CO ₂)	Frozen efficiency CO ₂ emissions (Mt CO ₂)	BAU CO ₂ emissions (Mt CO ₂)
Controls	11	5	4
Process Integration	11	27	19
CO ₂ removal	41	7	5
Synthesis	115	12	9
Ammonia reformer steam reforming	341	13	9
Ammonia reformer coal gasification	2254	18	13
Total		82	58

Table 9.2: Average costs of technologies and GHG emissions savings potential of ammonia fertilizer.

If all the measures would be implemented, the amount of CO₂ emissions saved, would represent 19% of CO₂ savings (82 Mt CO₂ avoided/434 Mt CO₂ released) for the frozen efficiency scenario and 15% of CO₂ savings (58 Mt CO₂ avoided/377 Mt CO₂ released) for the business as usual scenario. According to table 9.2, process integration is the technology that combines to be the cheapest (11 €/t CO₂) with the highest potential to save CO₂ emissions (27 Mt CO₂ on the FE scenario and 19 Mt CO₂ on the BAU scenario). Controls technology is as cheap as process integration technology but the potential of CO₂ savings is lower (5 Mt CO₂ in the FE scenario and 4 Mt CO₂ in the BAU scenario). After process integration technology, the following technology that provides more potential savings in terms of CO₂ emissions is ammonia reformer-coal gasification, saving 18 Mt CO₂ in the FE scenario and 13 Mt CO₂ in the BAU scenario; but it is very unlikely to be implemented due to its prohibited costs (2254 €/t CO₂) (Table 9.2).

9.3.3 Energy and GHG emissions savings of urea in the baseline scenarios

Regarding urea fertilizer, the results show that the average cost of the technology proposed is not cost-effective. Table 9.3 shows the costs in terms of €/GJ (CCE) and in €/t CO₂ (CCO₂). The energy savings of urea represent 6% of the overall energy consumption of urea in the frozen efficiency scenario and 5% in the business as usual scenario. The amount of CO₂ emissions that can be saved represent 7% of the total emissions being released in the frozen efficiency scenario and 5% in the business as usual.

	CCE (Discount rate 30%) (€/GJ)	Frozen Efficiency Energy Savings (PJ)	Business as usual Energy savings (PJ)	CCO ₂ (Discount rate 30%) (€/t CO ₂)	Frozen Efficiency CO ₂ emissions (Mt CO ₂)	Business as usual CO ₂ emissions (Mt CO ₂)
Urea - Pervaporation	2,609	51	31	45,260	3,488	2,226

Table 9.3: Average cost of urea technology, energy savings and CO₂ potential of urea fertilizer.

9.3.4 GHG emissions savings of nitric acid in the baseline scenarios

In the case of nitric acid, the average cost of the technology proposed is still quite expensive (4,759 €/ t CO₂), but not as expensive as urea technology for instance (45,260 €/ t CO_{2-eq}) (Table 9.3 and 9.4).

The potential savings of CO_{2-eq} emissions from nitric acid production are quite expressive. According to the results the savings potential are 90% of the overall CO_{2-eq} released for both scenarios.

	CCO _{2-eq} (Discount rate 30%) (€/ t CO ₂)	Frozen Efficiency CO _{2-eq} emissions (Mt CO _{2-eq})	Business as usual CO ₂ emissions (Mt CO _{2-eq})
Nitric Acid - HT CRM	4,759	69,591	58,958

Table 9.4: Average cost of nitric acid technology and the correspondent CO₂ savings.

9.4 Using a different methodology

Results show that for the three fertilizers the average costs of the technologies are positive. Therefore, on average there are not cost effective retrofit measures. However, it is possible to use a different methodology in which the costs of technologies are not averaged. Instead, the cost of each technology per country is accounted with the correspondent energy saving or amount of GHG emissions saved. Figure 9-4 depicts an example of the difference between the two methodologies. In the graph below, the costs of each technology are ranked from the cheapest to the more expensive in the Y axis and the cumulative energy savings are displayed on the X axis. Each technology is exhibited using a unique colour. Each colored line represents the costs of each technology for the 15 countries. In addition, a dashed line represents the cost supply curve of the average cost of each technology.

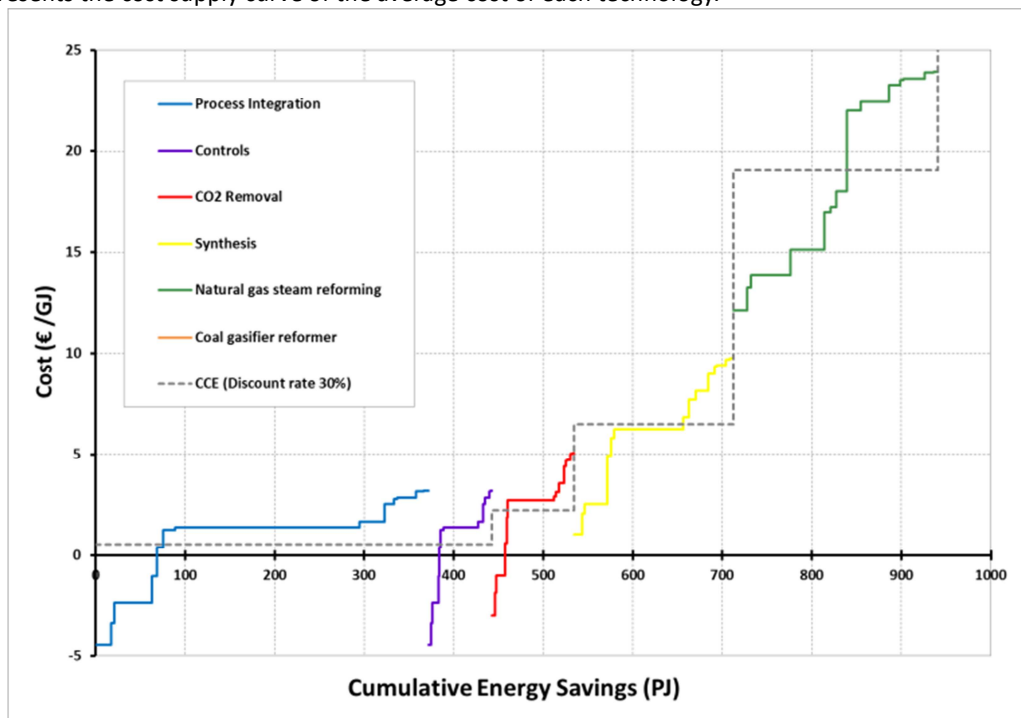


Figure 9.5: Costs of technologies and cumulative energy savings potential of ammonia fertilizer for the frozen efficiency scenario using a 30% discount rate.

The results show that for some countries, the costs of certain technologies are actually below zero. Figure 9.5 shows that part of the retrofit measures concerning the technologies: process integration, controls and CO₂ removal, incorporates cost-effective retrofit measures. Coal gasification technology was removed from the picture for a better perception. The energy savings of these cost effective retrofit measures are 69 PJ for process integration, 12 PJ for controls and 5 PJ for CO₂ removal technologies. In total, the cost effective

retrofit measures represent only 7,6% of the total potential energy savings of the ammonia fertilizer (frozen efficiency scenario with a 30% discount rate). This topic will be analyzed in more detail in the next sub-chapter.

9.5 The influence of retrofit measures and cost-effective retrofit measures on total energy consumption and GHG emissions for both scenarios

The impact of retrofit measures and cost-effective retrofit measures on the total energy consumption and on the total GHG released for both scenarios is analysed here in this sub-chapter. Cost effective retrofit measures were calculated according to the alternative methodology described in previous sub-chapter. The graphs of figures 9.6 and 9.7 show the impact of the cost effective retrofit measures and the retrofit measures on the overall energy consumption and GHG emissions for both scenarios.

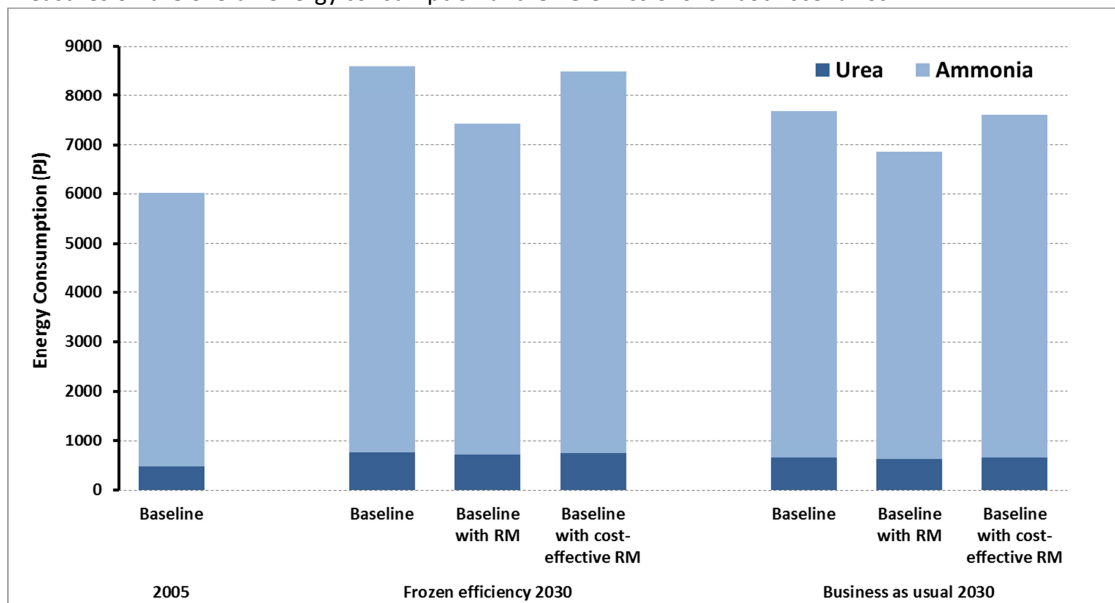


Figure 9.6: Impact of retrofit measures and cost-effective retrofit measures in both scenarios in terms of energy consumption.

From figure 9.6 it is visible that the situation differs slightly for the two future scenarios. If all the retrofit measures would be implemented the total energy consumption would drop to 13,7% in the frozen efficiency scenario (from 8602 PJ to 7424 PJ) and 10,7% in the business as usual scenario (from 7681 PJ to 6862 PJ). If the cost effective retrofit measures would be implemented than the energy consumption would drop 1,0 % in the frozen efficiency scenario and 0,8% in the business as usual scenario.

In the case of retrofit measures, ammonia is the fertilizer that contributes the most for the decrease of the energy consumption (14,4% decrease in the FE and 10,7% in the BAU), compared to urea fertilizer (6,6% in the FE and 4,7% in the BAU). In the case of cost-effective retrofit measures the situation is the same: ammonia is the fertilizer that contributes the most for its decrease (1,1% in the FE and 0,9% in the BAU) compared to urea (0,4% in the FE and in the BAU).

In the overall, the impact of the cost-effective retrofit measures is very low in both scenarios (around 0,9%); the impact of the retrofit measures is significantly higher (around 12% for both scenarios).

The following picture (Figure 9.7) depicts the impact of retrofit measures and cost-effective retrofit measures for both scenarios in terms of GHG emissions.

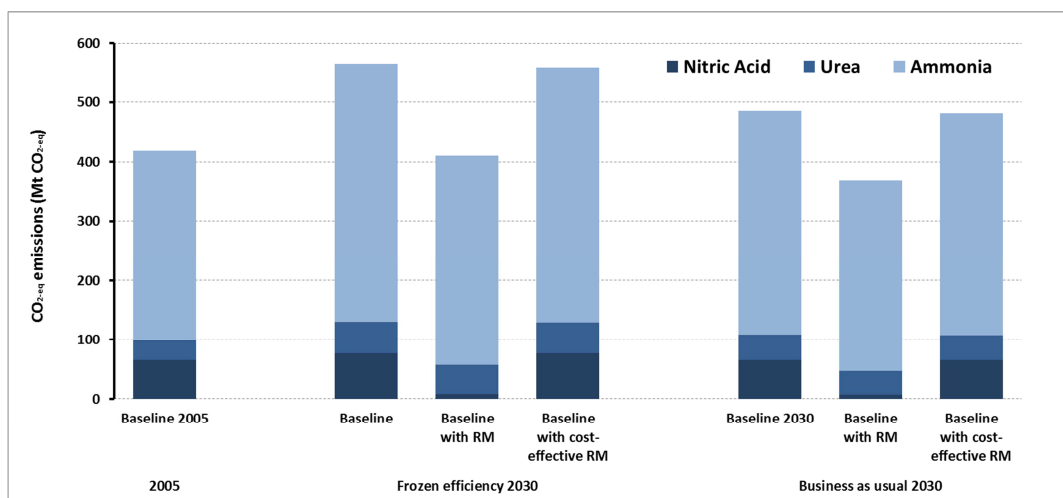


Figure 9.7: Impact of retrofit measures and cost-effective retrofit measures in both scenarios in terms of GHG emissions.

In agreement with the results, if all the retrofit measures would be implemented, the GHG emissions would fall 27,4 % in the frozen efficiency scenario and 24,4% in the business as usual scenario. The impact of retrofit measures in terms of GHG is higher than in terms of energy consumption. This is mainly due to the contribution of the GHG emissions potentially saved due to the implementation of N₂O abatement technologies for nitric acid production. The GHG emissions from nitric acid production on the baseline scenarios accounting with retrofit measures are expected to decrease 90% in both scenarios. The second biggest contributor is ammonia. The decrease of the GHG emissions by the retrofit measures concerning ammonia is 18,8% in the frozen efficiency scenario and 15,3% in the business as usual. The fertilizer that contributes the least for its decrease in the future scenarios is urea (6,6% in the FE and 5,25% in the BAU). The GHG emissions regarding the cost-effective retrofit measures represent only 1,01% in the frozen efficiency scenario and 0,85% in the business as usual. The major contributor for it is ammonia fertilizer, followed by urea fertilizer; there are not cost-effective retrofit measures regarding the GHG emissions due to nitric acid production.

9.6 Specific energy consumption of ammonia per country according to the different scenarios

The aim of this sub-chapter is to present the results of the specific energy consumption of each country for both scenarios and to acknowledge the technical potential of the specific energy consumption for the retrofit measures suggested for ammonia in this report. BAT levels for each country will be presented as a reference.

The cost-effective retrofit measures were not accounted because its impact is very low.

As previously showed in Table 7.2, the specific energy consumption (SEC) of each country was collected for the reference year 2005; it was defined that this data represents the SEC for the baseline in 2005 and the SEC for the frozen efficiency scenario in 2030.

The SEC for business as usual scenario was calculated proportionally to the amount of ammonia produced by the old plants and by the new plants and applying two different values of SEC for the old plants and for the new plants. Therefore, for the old plants, it was defined that the ammonia produced in 2030 by the old plants equals the amount of ammonia produced in 2005. The SEC of old plants decreases by 0,15% per year during 25 years by autonomous increase of energy efficiency. For the new plants, its production is expressed by the difference between the expected production in 2030 and the production in 2005; it was assumed that the new plants are operating at BAT levels.

It was defined the BAT SEC for China and India was different then for the other countries. The BAT value considered for China and India was calculated according to the mix fuel share of the country in 2005. It

was assumed that the other countries run on BAT levels based on 100% natural gas. No change in fuel share in 2030 was implemented in the model.

The energy savings were calculated multiplying the energy savings of each technology (in terms of GJ/t NH₃) by the percentage of applicability of each technology in each country. The percentage of applicability of each technology was decided in conversations with professor Worrell.

The SEC data presented in the following table is expressed in terms of GJ/t NH₃.

	Energy Savings	SEC (FE)	SEC with retrofit measures (FE)	SEC (BAU)	SEC with retrofit measures (BAU)	BAT	Technical Potential (FE)	Technical Potential (BAU)
Canada	2,67	34,40	31,73	33,13	30,46	27,00	-8%	-9%
China	7,32	51,32	44,00	46,58	41,20	38,70	-17%	-13%
Egypt	4,90	39,00	34,10	32,03	29,96	28,00	-14%	-7%
Germany	4,41	37,30	32,89	35,93	31,52	27,00	-13%	-14%
India	4,57	40,20	35,63	35,10	32,82	31,50	-13%	-7%
Indonesia	5,87	39,90	34,03	33,31	30,07	27,00	-17%	-11%
Iran	3,70	37,00	33,30	31,11	29,35	27,00	-11%	-6%
Netherlands	1,64	31,00	29,37	29,86	28,22	27,00	-6%	-6%
Pakistan	5,15	38,50	33,35	30,46	28,69	27,00	-15%	-6%
Poland	5,47	39,00	33,53	34,76	30,74	27,00	-16%	-13%
Russia	5,87	40,00	34,13	38,53	31,20	27,00	-17%	-23%
Saudi Arabia	2,45	36,00	33,55	30,00	29,04	27,00	-7%	-3%
Trinidad	4,01	36,90	32,90	32,57	29,96	27,00	-12%	-9%
Ukraine	5,47	39,00	33,53	35,43	31,07	27,00	-16%	-14%
United States	4,47	38,00	33,53	36,60	32,13	27,00	-13%	-14%

Table 9.5: Specific energy consumption of ammonia per country according to the different scenarios.

China, Indonesia and Russian are the three countries that combine having the highest specific energy consumption and the highest potential energy savings. The SEC of India is also quite high but the potential savings are not as expressive (Table 9.5). The results show that the previous three countries are also the ones with biggest technical potential for both scenarios. For instance in China the SEC accounting with the retrofit measures drops to 17% (from 51,32 to 44,00 GJ/t NH₃) in the FE scenario and 13% (from 46,58 to 41,20 44 GJ/t NH₃) in the BAU scenario; in Indonesia the technical potential represents 17% in the FE scenario and 11% for BAU. Russia presents the highest technical potential in the BAU scenario. Russia is the only country out of the 15, where the production decreases from 2005 to 2030. The SEC BAU of Russia only accounts with the SEC from the old plants which is lower that the SEC from the plants in the frozen efficiency scenario. When the energy savings from the retrofit measures are subtracted from the baseline SECs and the technical potential is calculated, the result shows that the technical potential of BAU is obviously higher than the technical potential of FE; due to the same reason Russia also has the highest technical potential of BAU out of the 15 countries.

Due to room constrains it was not possible to depict the different SEC of each 15 countries per scenario. Thus, it was decided to analyse graphically only the top four biggest producers of ammonia (China, India, Russia and The United States) and The Netherlands. The Netherlands is a high-tech developed country in ammonia plants based on natural gas, so the baseline of specific energy consumption for both scenarios is quite low and close to the BAT levels. The idea is that The Netherlands works as a reference in this analysis. Figure 9.8 depict the different values of specific energy consumption of ammonia for the five countries mentioned before.

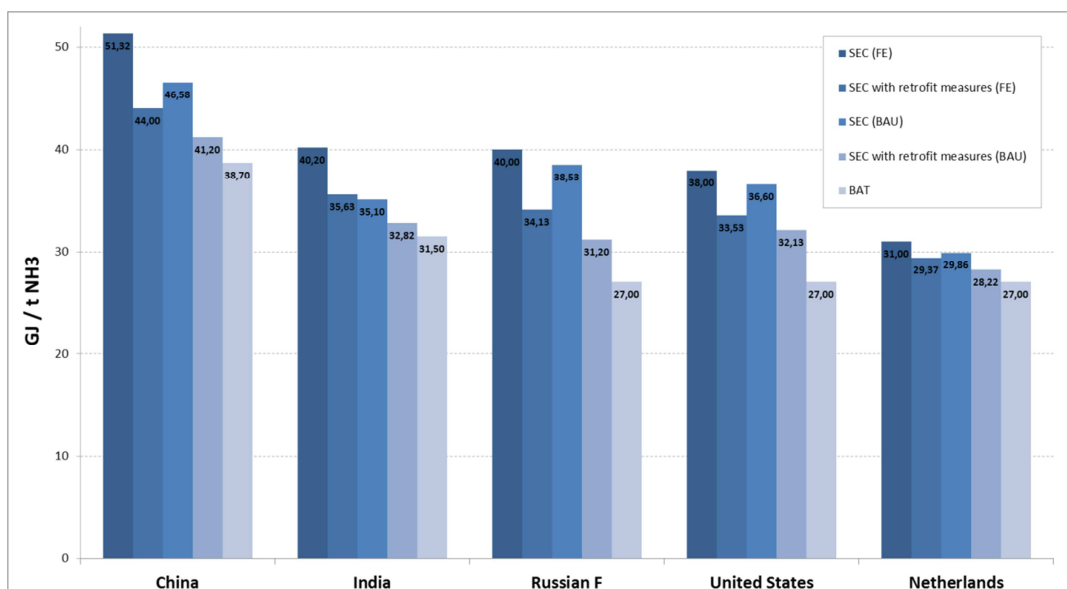


Figure 9.8: Specific energy consumption of ammonia for China, India and The Netherlands according to the different scenarios.

China is obviously the country with the highest energy consumption. The SEC of China is 39,6% higher than the SEC of The Netherlands for the frozen efficiency scenario since 78% of the ammonia plants in China use coal as a feedstock and fuel, which requires significantly more energy than a natural gas based plant. China also exhibits a high level of potential savings due to the extra retrofit measures suggested based on coal – coal gasification. The savings of this retrofit measure represent 34,5% of the total energy savings suggested. However coal gasification technology is very expensive so the probabilities of it to be implemented are low.

The SEC of India and Russia is quite comparable and quite high but for different reasons. In India, part of the fuel and feedstock used is oil which makes the ammonia production process more energy intensive. In Russia, although this country uses only natural gas in the ammonia production process, the current technology implemented is very old which increases the energy consumption level.

The reason why the United States does not present a level of SEC, such as The Netherlands, is due to the lack of applicability of new technology, just like in the case of Russia but in a lower degree.

If all the retrofit measures suggested could be applied in the BAU scenario, India and The Netherlands would be the closest countries to reach the BAT levels proposed. The SEC BAU is just 4% higher than the BAT level for both countries. The SEC BAU with retrofit measures for China is 6,1%. This is a very optimistic perspective because the implementation of coal gasification technology is quite unrealistic. If coal gasification measures would not be accounted the SEC BAU with retrofit measures would be 43,06 GJ/t NH₃ instead of 41,20 GJ/t NH₃. In this case China would become 10,01% far from the BAT level instead of 6,1% as first calculated. This approach seems more reasonable.

In consonance with the graph, United States and Russia are the countries more distant to reach BAT values compared to the SEC BAU accounting with the savings from the retrofit measures, 16% and 13,5% difference respectively. These results were expected since these countries are the ones where the implementation of new technology is lacking the most.

9.7 Specific energy consumption of urea per country according to the different scenarios

The calculations concerning urea fertilizer followed the same concept than ammonia fertilizer, except the calculation of BAT. In the case of urea, the BAT level did not account for the mix fuel share of China and India. The cost-effective retrofit measures are also not presented. Table 9.7 below is similar to table 9.6 presented in the previous sub-chapter. It shows the same results but regarding urea fertilizer.

	Total Sec savings	SEC (FE)	SEC with retrofit measures (FE)	SEC (BAU)	SEC with retrofit measures (BAU)	BAT	Technical Potential (FE)	Technical Potential (BAU)
Canada	0,2	3,8	3,6	3,6	3,5	3,2	-4%	-4%
China	0,3	4,7	4,4	4,1	3,9	3,2	-7%	-6%
Egypt	0,3	4,7	4,4	3,7	3,6	3,2	-7%	-4%
Germany	0,2	3,8	3,6	3,6	3,5	3,2	-4%	-4%
India	0,3	4,7	4,4	3,8	3,7	3,2	-7%	-4%
Indonesia	0,3	4,2	3,9	3,7	3,5	3,2	-8%	-5%
Iran	0,3	4,7	4,4	3,8	3,7	3,2	-7%	-4%
Netherlands	0,2	3,8	3,6	3,6	3,5	3,2	-4%	-4%
Pakistan	0,3	4,7	4,4	3,6	3,5	3,2	-7%	-3%
Poland	0,3	4,2	3,9	3,8	3,6	3,2	-8%	-6%
Russian F	0,3	4,2	3,9	4,3	3,9	3,2	-8%	-10%
Saudi Arabia	0,2	3,8	3,6	3,4	3,3	3,2	-4%	-2%
Trinidad	0,2	4,2	4,0	3,8	3,7	3,2	-4%	-3%
Ukraine	0,3	4,2	3,9	3,9	3,6	3,2	-8%	-7%
United States	0,3	4,2	3,9	4,0	3,7	3,2	-8%	-8%

Table 9.6: Specific energy consumption of urea for China, India and The Netherlands according to the different scenarios.

In the case of urea fertilizer, the data regarding the energy intensity and the energy savings per ton of urea is more homogeneous among countries.

In general, the technical potential of urea is lower than the technical potential of ammonia reaching a maximum of only 10% in Russia BAU scenario compared to 23% for the same country and for the same scenario.

The countries with the highest technical potential differ when compared to ammonia case. For the frozen efficiency scenario these countries are Indonesia, Poland, Russia, Ukraine and United States (8%); for the BAU scenario Russia is the country with the highest technical potential. The reason why the technical potential of Russia is higher in the frozen efficiency scenario than in the business as usual scenario for urea fertilizer is the same as for ammonia fertilizer.

The four biggest producers of urea are China, India, Indonesia and United States. The Netherlands is one of the countries with the lowest energy consumption of urea. Figure 9.9 is depicted in order to become clear how the energy consumption might change if the savings of retrofit measures would be to be applied on both scenarios.

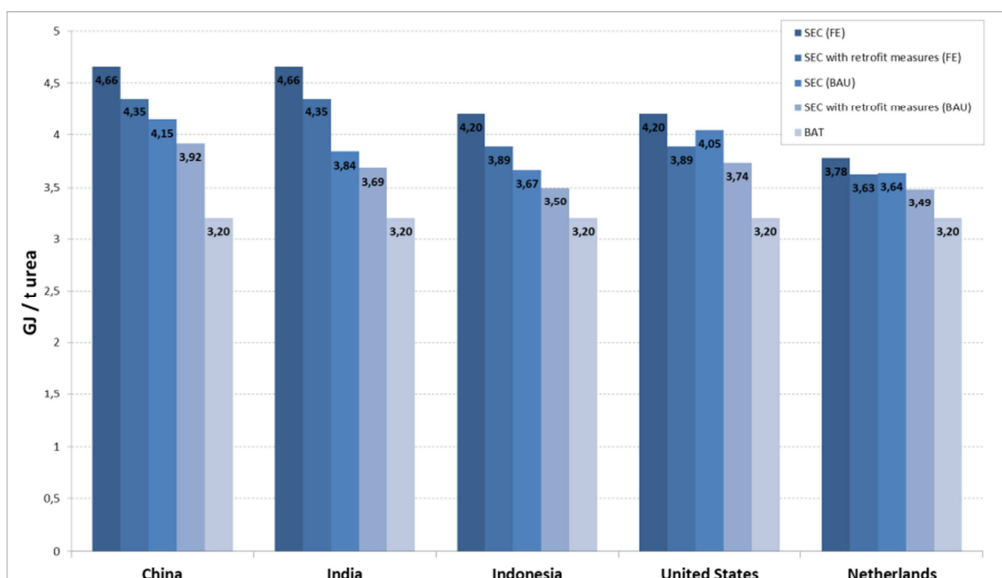


Figure 9.9: Specific energy consumption of urea for China, India, Indonesia, United States and The Netherlands according to the different scenarios.

With figure 9-9 it is now graphically visible that the data regarding energy consumption and energy savings of urea is more uniform than in the case of ammonia. China and India share the same high SEC in the frozen efficiency scenario. Indonesia and the United States have what can be called an average SEC for the frozen efficiency scenario. The SEC of The Netherlands on the frozen efficiency scenario is 31% lower than the same SEC of China and India and 10% lower than the same SEC of Indonesia and United States. The difference between the SEC BAT level and the SEC BAU with retrofit measures is in general higher than in the case of ammonia. In order to reach SEC BAT levels China would have to drop its SEC by 18,3%, United States 14,33% and India 13,22%. Indonesia and The Netherlands are the countries where this difference is less expressive 8,45% and 8,18%, respectively. The reason for this gap is because there is only one technology and the savings regarding this technology are not so significant: even if this retrofit measures would be implemented, the savings of it would not be enough to reach BAT levels in the most optimistic scenario, the business as usual scenario.

9.8 Emission reduction of the top four nitrogen fertilizers countries and The Netherlands

In this sub-chapter it is analyzed the potential reduction of GHG emissions for the four largest producers of nitrogen fertilizers (China, India, Russia, United States) plus The Netherlands. The Netherlands was chosen as a reference of a high-tech developed country. These five countries account for 79% of the GHG emissions expected to be emitted in 2030 in the frozen efficiency scenario. The potential GHG emissions reduction is presented according to the emissions released by each of the three fertilizers in study: ammonia, urea and nitric acid for the two future scenarios. Figure 9.10 depicts the results.

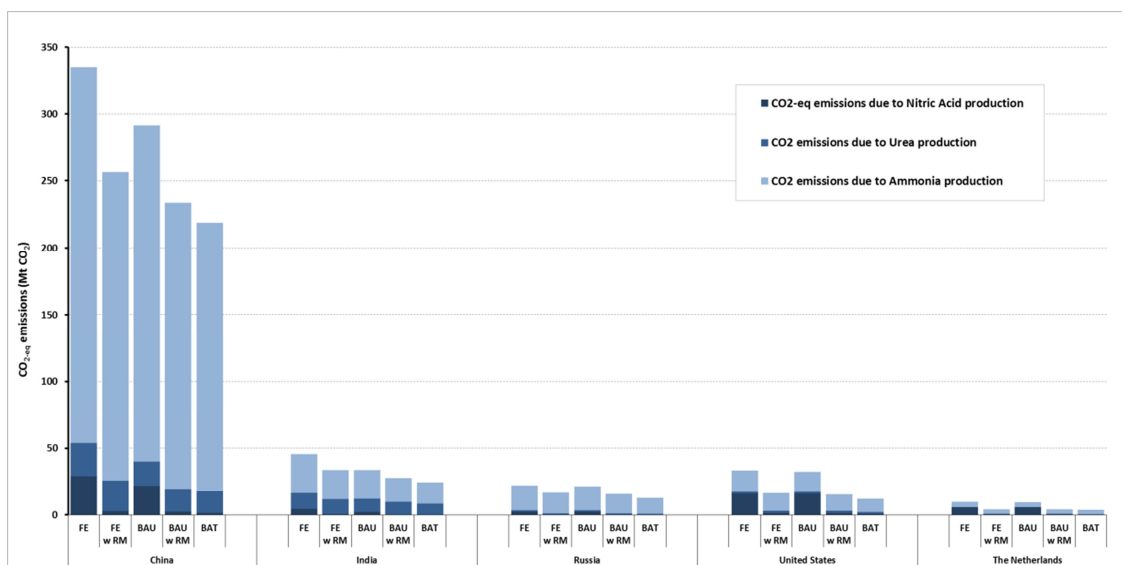


Figure 9.10: Emission reduction of the top 4 nitrogen fertilizers countries and The Netherlands.

The results show that China will be emitting 335 Mt CO₂ in 2030 frozen efficiency scenario. China will be responsible for 59% of the GHG emissions emitted in the world (in this case the world is represented by the 15 countries proposed in study). GHG emissions generated due to ammonia production will be playing a major role (84%), followed by GHG emissions due to nitric acid (9%) and urea (7%). For the same scenario, the global GHG emissions for China with retrofit measures can potentially decreased by 24%. One third of this decrease is due to GHG emissions released by nitric acid production. The GHG emissions concerning the business as usual scenario are expected to reach 251 Mt CO₂, 10% less than the GHG released in the frozen efficiency scenario. In the BAU scenario with the implementation of the retrofit measures the GHG emissions can potential decrease by 20%. GHG emissions due to ammonia production play also a major role in the potential overall decrease, just like in the FE scenario, but in a less degree (65%); GHG emissions due to nitric acid contribute exactly the same as in the FE scenario (33%) and GHG emissions due to urea contribute much less than in the FE scenario, only 2%.

India and United States are also major contributors of the GHG emissions from nitrogen fertilizers but in a lower degree. The GHG emissions expected to be released in the frozen efficiency scenario by India and the United States represent 8% (45,55 Mt CO₂) and 5,9% (33,32 Mt CO₂), respectively, in the overall GHG emissions of the 15 countries. India does not produce significant amounts of nitric acid, thus its GHG emissions reduction potential. It is mainly due to the implementation of retrofit measures of ammonia. The contribution of ammonia in the GHG emissions reduction potential is 61% for both scenarios; GHG emissions due to nitric acid contribute 32%, and GHG emissions due to urea contribute 7% also in both scenarios. United States is the second major country releasing GHG emissions due to nitric acid (15,81 Mt CO₂-eq in FE scenario); the first one is China releasing 29,20 Mt CO₂-eq. In 2030, the United States is expected to emit evenly quantities of GHG emissions due to ammonia and nitric acid in both scenarios. The GHG emissions reduction potential of the United States is higher than India, 51% in the FE and 52% in BAU scenarios against 26% in FE and 18% in BAU scenarios. The reason behind this difference is the fact that the retrofit measures suggested for nitric acid lead to higher rates of GHG emissions reduction potential (nitric acid contribution is 97% in FE and 83% in BAU against ammonia 3% in FE and 16% in BAU). Russia is a country that produces mainly ammonia. 84% of the expected GHG emissions in 2005 and also in 2030 are due to ammonia production. GHG emissions due to nitric acid and urea represent 11% and 5% in 2005 and 2030. Russia is a country with very old technology and its production is expected to decrease. The GHG emissions reduction potential is around 26% in both scenarios and it is mainly due to implementation of retrofit measures of ammonia (60%) and nitric acid (39%).

From figure 9.10 it is obvious that the Netherlands is the country that releases fewer amounts of GHG emissions. However it is the fourth country out of 15 that releases the highest emissions due to nitric acid.

The GHG emission reduction potential is due to nitric acid, with expressive 95% of contribution in both scenarios; contrasting with only 5% due to ammonia. The Netherlands is a country where most of the technologies regarding ammonia production are already implemented. So the focus on this country should concern mainly the nitric acid technologies so the overall GHG emissions will decrease significantly. If all the retrofit measures would be implemented in the business as usual scenario, the countries chosen would still be far in some cases to reach the BAT levels. In China this difference is the lowest (6%), but this is accounting for the retrofit measures of coal gasification technology. This is not a very realist approach because coal gasification technology is very expensive. If this technology would not be account China would be 20% far from the BAT levels. The difference between the BAU with retrofit measures and the BAT level for United States and Russia is also around 20%. For India this difference is only 11%; and as expected the Netherlands this difference is the smallest with only 10%.

10 Sensitivity analysis

The model developed in this research involves a certain number of parameters that are subject to uncertainty. The sensibility of certain of these parameters was explored: discount rate and fuel prices. The calculations measure the change on the energy and GHG emissions of the cost-effective retrofit measures when these parameters are modify.

10.1 Influence of discount rate

In general, stake holders are interested in projects with a short payback time and consequently a high discount rate. To illustrate this typical behaviour a high discount rate of 30% was chosen as a reference for this research. For the sensitivity analysis calculations discount rates of 20%, 10% and 5% were used.

Table 10.1 shows the results of the sensitivity analysis regarding ammonia. Figures 10.1 and 10.2 depict the ammonia's cost-supply curves using different discount rates for the frozen efficiency and business as usual scenarios. The pictures illustrate the costs of each technology and the amount of energy saved per country for each scenario.

		Frozen efficiency - Retrofit Potential		Business as usual - Retrofit Potential	
		Energy	GHG emissions	Energy	GHG emissions
Ammonia	20% Discount rate	0,37	0,36	0,40	0,39
	10% Discount rate	4,19	5,34	4,04	5,32
	5% Discount rate	6,51	7,83	6,37	7,87

Table 10.1: Results of sensitivity analysis on discount rates for ammonia urea.

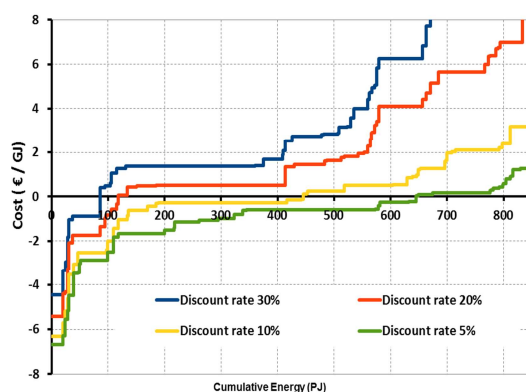


Figure 10.1: Ammonia's cost supply curve (FE scenario).

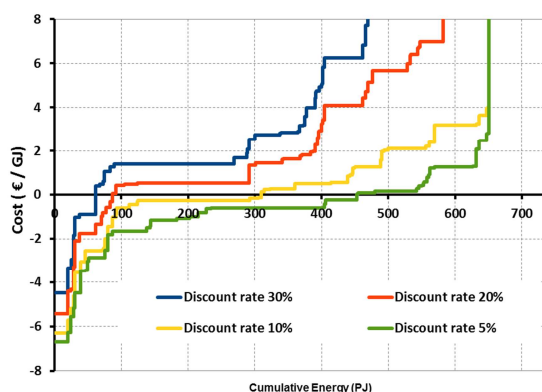


Figure 10.2: Ammonia's cost supply curve (BAU scenario).

The results of the change in energy savings and in GHG emissions are quite alike for both scenarios. The results show that in both scenarios there is a significant difference on the energy savings and GHG emissions regarding cost-effective measures when using discount rates of 10% and 5%. For instance, using a 10% discount rate it would be profitable to implement technologies like process integration, controls and CO₂ removal in 20 more countries; and using a 5% discount rate, the fourth most expensive technology, ammonia steam reformer, could be implemented in 8 countries. The growth in the number of countries where cost-effective measures can be implemented is the same for frozen efficiency scenario and business as usual scenario but the correspondent energy savings are different.

Table 10.2 shows the sensitivity analysis results of urea. Figure 10.4 and 10.5 illustrate the abatement cost curves of urea for the different discount rates.

		Frozen efficiency - Retrofit Potential		Business as usual - Retrofit Potential	
		Energy	GHG emissions	Energy	GHG emissions
Urea	20% Discount rate	4,55	5,06	2,29	2,55

10% Discount rate	6,16	6,67	2,87	3,12
5% Discount rate	14,73	18,86	8,93	11,84

Table 10.2: Sensitivity analysis results of urea.

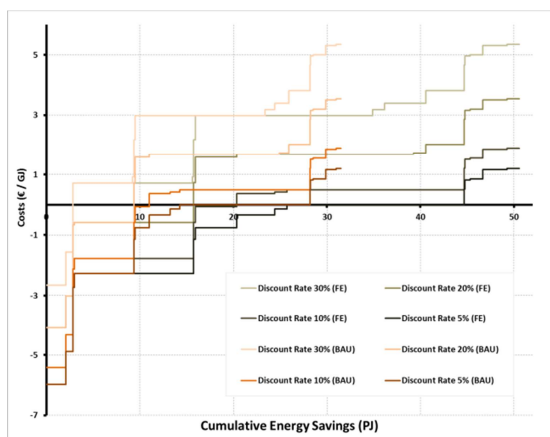


Figure 10.3: Urea's cost supply curve (FE and BAU scenario).

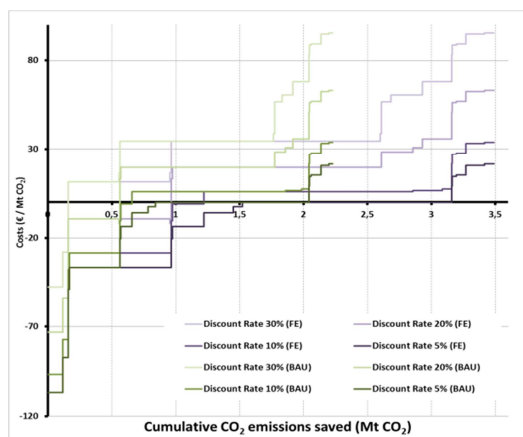


Figure 10.4: Urea's cost abatement curve (FE and BAU scenario).

The results show that in the case of GHG emissions the differences in between scenarios concerning the energy savings are quite more significant than in the previous case of ammonia: the changes in frozen efficiency scenarios are much higher than in the business as usual scenario.

In the case of urea there is only one technology in study: pervaporation. Therefore the results show that lowering the discount rate will allow more countries to implement this technology directly because it would become a cost-effective measure. For a 20% discount rate used the change is not so significant. But when 10% and 5% discount rate is used then the changes increase considerably. For example, using a 30% discount rate only United States and Canada would present pervaporation as a cost-effective measure, but if a 5% discount rate is used then it can be implemented in eight more countries: Germany, The Netherlands, India, Poland, Pakistan, Indonesia, Ukraine and China; meaning that 66% of the countries could now implement this technology in a cost-effective way against 13% initially.

As previously mentioned, the nitric acid technologies calculated using a discount rate of 30% were not cost-effective; when recalculated for lower discount rates they became cheaper but still not cost-effective.

10.2 Influence of energy prices

It was defined that energy prices remain constant until 2030. This assumption has consequences in terms of energy and GHG emissions savings. Table 10.3 shows the change in the outcome if fuel prices would increase or decrease 25% for ammonia and urea fertilizers.

		Frozen efficiency - Retrofit Potential		Business as usual - Retrofit Potential	
		Energy	GHG emissions	Energy	GHG emissions
Ammonia	25% increase in Fuel Prices	0,34	0,33	0,35	0,35
	25% decrease in Fuel Prices	-0,65	-0,67	-0,51	-0,53
Urea	25% increase in Fuel Prices	4,55	5,06	2,29	2,55
	25% decrease in Fuel Prices	-0,27	-0,27	-0,27	-0,27

Table 10.3: Results of sensitivity analysis on fuel prices for ammonia and urea.

In the case of ammonia the results on table 10.3 show that for both scenarios the energy savings do not change considerably when the fuel prices increase: the measures for an extra six more countries become cost-effective including technologies like synthesis, CO₂ removal, controls and process integration. Even with such an increase on the fuel prices the expensive technologies do not become enough cheaper to

become cost-effective. For a fuel price decrease the change is quite more significant meaning that for a substantial amount of countries the technologies measure will become non-cost-effective. For the current applied fuel prices 8 countries could apply cost effective measures and with a fuel price decrease this only valid for 3 countries. The results regarding the GHG emissions if prices change are comparable to the ones concerning energy savings but not so dramatic.

In the case of urea the results are quite more expressive: if the fuel price increase there is a drastically change. Using the current fuel prices the results show that pervaporation is cost-effective measure for the US and Canada; if fuel prices increase pervaporation becomes cost-effective for a few more countries including India, a country that allocates high amounts of energy savings and GHG. Fuel prices decrease make pervaporation more expensive only enabling only United States with cost-effective measure. The calculations give the same result for both energy saving and GHG because United States has aggregate the same energy savings and GHG emissions for the frozen efficiency and business as usual scenario.

11 Discussion

The static model devolved on this research aimed to calculate the global CO₂ abatement potential in the nitrogen fertilizer industry up to 2030. In order to do it a certain number of assumptions were taken and specific sources were chosen. The options taken have crucial impact on the final results. This chapter aims to compare certain decisions made and the results obtained with other studies.

11.1 Nitrogen fertilizers: production and production growth rate

Each country has allocated production data of ammonia and urea and CO_{2-eq} emissions from nitric acid. For ammonia and urea the data was based mostly from Yara's report and nitric acid mostly from National non- CO₂ Greenhouse gases reports (UNFCCC). However IFDC also provided the same type of information for ammonia. The production growth rate of the three nitrogen fertilizer production was based on IEA report that presents ammonia's fertilizer trends in 2030 in terms of consumption per capita and on a region level. It could also had been an option to use the per year growth rate of ammonia and urea suggested on Yara's report or to extrapolate the data from IFDC; for nitric acid it could also had been used the annual growth rate proposed in Ramirez et al 2003. The production data and the production growth rate were the first assumptions to be established and the way they were defined had direct consequences on the baseline scenarios for 2005 and 2030.

11.2 Fuel mix, specific energy consumption and fuel prices

As previously mentioned the nitrogen fertilizer production involves the use of fossil fuels. Although for ammonia's production, natural gas is the preferable fossil fuel, not all the countries have it available. Therefore the share of fossil fuels for the use of ammonia and urea varies per each country. In this research these data was gathered from ECN 2009 because the data provided was more recent then other papers and it covered a wide range of countries. However, there are other papers providing the some information. Table 11.1 shows the data used in this report with other two papers: IEA tracking 2007 and Zhou et al 2009. The fuel mix is allocated to the total GHG emissions released calculations and the calculations regarding GHG emissions savings, therefore these differences would entail different results in the model.

	Model	IEA 2007	Zhou et al 2009
Western Europe	100% natural gas	5% oil 95% natural gas	
China	78% coal 22% natural gas	70% coal 10% oil 20% natural gas	71% coal 8% oil 21% natural gas
India	70% oil 30% natural gas	50% oil 50% natural gas	

Table 11.1: Fuel mix share differences.

In order to be more coherent, similar strategy was used for the specific energy consumption of ammonia and urea data. As much as possible data was gathered from the same paper ECN 2009. Nonetheless there are other papers mentioning the same type of data: Zhou et al 2009, Benchmarking energy efficiency and carbon dioxide emissions - CFI 2008; Recent Efforts in Energy Conservation in Ammonia and Urea Plants Nand et al 2008.

Natural gas is the primary feedstock in ammonia production and, depending on its price; it makes up roughly 75-90% of cost of producing ammonia. Fuel price data was used when the financial benefits of CSC were calculated. Fuel prices have a huge impact on the final results. For this research the source used was mostly from American Chemical Society Slides 2005; although not so complete data is also available in: Potash Corp 2009.

11.3 Methodology and technological options

The report Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC): Industry & refineries sector (October 2009) identifies the potential costs of technical control options to reduce greenhouse gas emissions across all European Union's sectors and Member States in 2020 and 2030. Since its approach is quite a similar to this research, it is interesting to illustrate, compare and contrast the methodology and the results obtained. Table 11.1 shows some of the strategies implemented on both surveys. Just like in this dissertation, SERPEC-CC uses a bottom-up approach to determine the potential for energy efficiency improvements. In addition two scenarios were developed: PRIMES 2007-baseline scenario, which includes autonomous technology improvements and further implementation of before-2007 and Frozen Technology Reference Level scenario, which holds all the characteristics of the PRIMES 2007-baseline scenario except the technology characteristics of sectors which remain 'frozen' at the 2005. This report is meant to be used by policy makers so it is important to compare one scenario that account for technology developments and another one where autonomous and policy-driven efficiency improvements are not taken included. Cost-supply-curves are also build up and the costs of abatement measures are calculated just like in this research. The stock turnover assumptions regarding the old and new capacity go further in complexity than in this model.

		SERCPEC project	Model
Average growth year ammonia		1,5%	Specific for each country
Average growth year urea		1,5%	Specific for each country
Average growth year nitric acid		1,5%	Specific for each country
SEC BAT ammonia		28 GJ/t ammonia	27 GJ/t ammonia
Technology ammonia	measures		
Reforming ammonia:	section	Energy savings	Large improvements: 4GJ/t ammonia Moderate investments: 1,4 GJ/t ammonia
		Costs	Large improvements: 24€/t ammonia Moderate improvements: 5€/t ammonia
		Rate of implementation	10% large improvements 30% moderate improvements
CO ₂ removal	section	Energy savings	0,9 GJ/t ammonia
		Costs	15 €/t ammonia
		Rate of implementation	30%
Synthesis		Energy savings	0,5 GJ/t ammonia
		Costs	6€/t ammonia
		Rate of implementation	90%
Controls		Energy savings	0,7 GJ/t ammonia
		Costs	6€/t ammonia
		Rate of implementation	30%
Process integration		Energy savings	3 GJ/t ammonia
		Costs	30 €/t ammonia
		Rate of implementation	10%
Total savings ammonia		Total energy savings ammonia	28%
		Total CO ₂ savings ammonia	28%
			11% (BAU) 15% (BAU)
Technology urea	measures	Total energy savings	40%
		Total CO ₂ savings	24%
		Costs	30 €/t urea
		Rate of implementation	20% in EU 15 50% in the EU countries join later
			5% 15 €/t urea 50% high tech developed countries and 100% for the others
Technology nitric acid	measures	Total CO ₂ savings	92% up to 2020 96% up to 2030
		Costs	< 1€/t CO ₂ -eq
		Rate of implementation	100%
			89% 2,25€/t CO ₂ -eq 100%

Table 11.2: Comparison with SERPEC study.

SERPEC project is focused on European country members and this study is focus on 15 countries that make up 80% of world nitrogen production. Since it has a country level based certain features are not able to be compared. For instance, the average growth year of each fertilizer is constant on SERPEC but in this model it differs by each country and it is based on the growth consumption rate of ammonia IEA 2007. The same applies for the rate of implementation and the costs. In table 11.1 costs are not showed with the adopted version from region cost multipliers Gielen 2003. However it is relevant to mention because the authors from SERPEC use the same paper as a reference to define the savings and costs of each technology measure of ammonia: Raqfiqul et al 2005; their interpretation is different from the one implemented in this model (Table 11.1). They also do not include CCS as a technological option for ammonia because they only consider technological options commercially available today. Plus the costs and savings of urea proposed in SERTEC were defined using a combination of different literature just like in the case of this model. In the case of nitric acid fertilizer they present a general cost for the technologies presented without specifying which one will be implemented.

11.4 Energy and GHG emissions abatement potential

Apart from nitric acid, the total energy and CO₂ savings results obtained from SERPEC are more optimistic than the ones this model presents (table 11.1). In this model the percentage of total energy savings of ammonia is 11% (BAU) and the correspondent CO₂ savings reach 15% (BAU). Accounting with urea and nitric acid the energy savings represent 11% (BAU) and the CO₂ savings represent 24% (BAU). The other reports, IEA 2007 and IFA 2009 also expect more confident results in terms of savings than the ones this model obtained. IEA reports that 20% of energy (1 EJ) can be saved if best available technology is applied in ammonia production; IFA states that the global energy savings potential of ammonia facilities, based on natural gas, could reach around 15%; in addition the overall potential for reducing greenhouse gases emissions (accounting carbon dioxide and nitrous oxide emissions) could reach more than 25% (and possibly as much as 40% if BAT becomes the norm).

12 Conclusion

This dissertation aimed to study the global abatement potential of nitrogen fertilizer industry up to 2030. In order to acknowledge it, the present situation concerning the main nitrogen fertilizers in use was investigated, current and future technologies were researched, and assumptions were made to forecast the future situation of nitrogen fertilizers with respect to potential energy savings and GHG emissions reductions.

To reach the goal proposed and to answer the questions initially proposed several steps were taken. First a data base of the major nitrogen producing countries that make up 80% of global production was created. The data concerned the energy use, the energy intensities, the GHG emissions and intensities of the three major fertilizers: ammonia, urea and nitric acid. Moreover the current technology status, the technological options to increase energy efficiency and reduce GHG emissions and the rate of its implementation on these countries, was analysed. Besides the baseline scenario on 2005 two other scenarios were defined to contrast and compare the forthcoming situation up to 2030: frozen efficiency scenario, where the production refers to the situation in 2030 but it remains constant as in 2005 in terms of technological development; and the business as usual scenario where the old production is expected to increase its efficiency and the new production is assumed to run on BAT levels.

The results show that ammonia is the biggest nitrogen fertilizer. According to the model, its production is expected to increase 30% from 2005 (126Mt) to 2030 (179Mt). China is the biggest contributor (42%) followed in a much lesser degree by India (13%), Indonesia (7%), Russia and US (6%) (data production 2030). In 2005, the total energy consumption involved on the nitrogen fertilizer production process is 6014 PJ, in which ammonia represents 92% of it (5532 PJ). From 2005 to 2030 energy consumption increases by 43% in the frozen efficiency scenario (8602 PJ) and by 28% in the business as usual scenario (7681 PJ). The energy savings of all the retrofit measures make the total energy consumption drop to 13,7% in the frozen efficiency scenario (from 8602 PJ to 7424 PJ) and 10,7% in the business as usual scenario (from 7681 PJ to 6862 PJ). The energy savings of the cost effective retrofit measures are not representative: the energy consumption would drop 1,0 % in the frozen efficiency scenario and 0,8% in the business as usual scenario.

The GHG emissions released in 2005 due to nitrogen fertilizers reached 418 Mt CO₂. The total GHG emissions are expected to increase 26% from 2005 to 2030 in the frozen efficiency scenario (564 Mt CO₂ in FE), and 14% in the business as usual scenario (486 Mt CO₂ in BAU). The situation of the countries that have the biggest impact in terms of GHG emissions for ammonia and urea is similar as energy consumption mentioned previously; nitric acid situation is different because the biggest producers are China (32%), Germany (17%) and United States (24%). The global CO₂ abatement potential, accounting with the retrofit measures chosen, represent a 27,4% decrease in the frozen efficiency scenario and 24,4% in the business as usual scenario. The impact of retrofit measures in terms of GHG is higher than in terms of energy consumption mainly because nitric acid retrofit measures are expected to decrease 90% in both scenarios.

Using a 30% discount rate most of the technologies are too expensive and cost effective retrofit measures are insignificant. If lower discount measures are applied the results change dramatically for both scenarios and technologies became much more affordable for ammonia and urea. Nitric acid technologies remain very expensive.

The number of technological measures included in this research was quite limited due to lack of data regarding technology prices. The global energy savings and the global GHG abatement potential scenario would have been different if more technologies had been aggregated to the survey.

13 References

FAO (2003), "World Agriculture: Towards 2015/2030 – An FAO perspective (Jelle Bruinsma, ed.) Earthe Publications, London, United Kingdom.

IFA (2009), "Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainably", Fits Edition, Paris, France.

EFMAa (2000), "Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry Booklet No. 1 of 8: PRODUCTION OF AMMONIA 2000" European Fertilizer Manufacturers' Association, Brussels, Belgium.

Apodaca L., (2009) "Nitrogen (fixed) – Ammonia", U.S Geological Survey, Mineral Commodity Summaries.

YARA (2008), "FERTILIZER INDUSTRY HANDBOOK".

J. Pérez-Ramirez, F. Kapteijn, K. Schöffel, J.A. Moulijn, (2003), "Formation and control of N₂O in nitric acid production Where do we stand *today?*" Applied Catalysis B: Environmental 44 117–151.

IPCC (2001), "Technical Summary of the Working Group I Report (2001)".

European Commission - Integrated Pollution prevention and Control (2006), "Reference Document on Best Available Techniques for the Manufactured of Large Volume Inorganic Chemicals – Ammonia, Acids Fertilizers" (BREF).

IFA (2008), "Ammonia production", <http://www.fertilizer.org/ifa/HomePage/SUSTAINABILITY/Climate-change/Emissions-from-production.html> (December 2011).

UNEP (1998), "Part 1The Fertilizer Industry's Manufacturing Processes and Environmental Issues" Technical report number 26 part 1, France.

Worrel E., Blok K., (1994) "Energy savings in the nitrogen fertilizer industry in The Netherlands", Energy Vol.19 No. 2, Pp. 195-2W, Elsevier Science Ltd, Great Britain.

EFMAb (2000), "Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry Booklet No. 5 of 8: PRODUCTION OF UREA and UREA AMMONIUM NITRATE 2000".

EFMAc (2000), "Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry Booklet No. 2 of 8: PRODUCTION OF NITRIC ACID".

IEA (2007) "Tracking industrial energy efficiency and CO₂ emissions", France.

Raqfiqul I., Weber C., Lehmann B., Voss A., (2005) "Energy efficiency improvements in ammonia production – perspectives and uncertainties", Energy Vol 30.

Nieuwlaar, E. (2001), "ICARUS – 4 – Sector study for chemical industry" NWS-E-2001-19, Utrecht, The Netherlands.

Saygin, D., Patel M., Tam C., Gilen D. (2009), "Chemical and Petrochemical Sector: Potential of best practice technology and other measures for improving energy efficiency" OECD/IEA, Paris, France.

SERPEC-CC (2009), "Sectoral Emission Reduction Potentials and Economic Costs for Climate Change – Industry & refineries sector", Ecofys JRC – IPTS.

Kongshaug G., (1998), "Energy consumption and green house gas emissions in fertilizer production, IFA , Marrakech, Marroc.

IEA (1998), "Mapping the energy future", Paris, France.

Worrel E., Ramesohl S., (2004), "Advances in energy forecasting models based on engineering economics", Annual Review Environmental Resources, vol 29 pp.345-381.

Beer J. (1998), "Potential for industrial energy efficiency improvement in the long term", thesis, Utrecht, The Netherlands.

Bartels J., Pate M., (2008), "A feasibility study of implementing an Ammonia Economy", Iowa State University, United States.

Zhou W. et al (2010), "CO2 emissions and mitigation potential in China's ammonia industry", Energy Policy, Elsevier Ltd.

Beer J., Wees M.T., Worrell E., Blok K. (1994), "The potentials of energy efficiency improvement in The Netherland from 1990 to 200 and 2015, Utrecht University, The Netherlands.

Lako P., (2009), "Energy conservation potential of the nitrogen fertiliser industry", ECN, The Netherlands.

US EPA (2006), "Industrial Processes" – Table 1-5, http://www.epa.gov/climatechange/Downloads/EPAactivities/GM_SectionIV_Industrial.pdf, December 2011.

Gielen D., (2003) "Uncertainties in relation to Co2 capture and sequestration. Preliminary results." IEA, France.

IPCC 2010 "Terms used in IPCC climate change scenarios", Switzerland.

ETTI- IEA 2009 "Energy technology transitions for industry – Strategies for Next Industrial Revolution", <http://www.iea.org/textbase/nppdf/free/2009/industry2009.pdf>, December 2011

Blok, K., (2007) "Introduction to energy analysis", Techne Press Amsterdam.

Ramírez C.A., Worrel E., (2006) "Feeding fossil fuels to the soil – An analysis of energy embedded and technological learning in the fertilizer industry", Resources, Conservation and Recycling Vol.46.

Jasinski S., Kramer D., Ober J., Searls J., (1999), USGS Fact Sheet FS -155-99: "Fertilizers-Sustaining Global Food Supplies", U.S Geological Survey.

Breierova, L., Choudhari, M. (1996) "An introduction to sensitivity analysis", Massachusetts Institute of Technology, retrieved 1-12-2008 from <http://sysdyn.clexchange.org/sdep/Roadmaps/RM8/D-4526-2.pdf>

Breierova, L., Choudhari, M. (1996) "An introduction to sensitivity analysis", Massachusetts Institute of Technology, retrieved 1-12-2008 from <http://sysdyn.clexchange.org/sdep/Roadmaps/RM8/D-4526-2.pdf>

Worrell E., Galitsky C., (2005) "Energy efficiency improvement and cost saving opportunities for petroleum refineries – An energy start guide for energy and plant managers", Ernest Orland Lawrence Berkeley National Laboratory.

EPA 2006, "Global Anthropogenic Emissions of Non-CO2 Greenhouse Gases: 1990-2020" (EPA Report 430-R-06-003) <http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html> (December 2011).

IFDC (2008), "IFDC An international Center for Soil Fertility and Agricultural Development - Worldwide ammonia Capacity Listing by Plant", Alabama, United States.