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Evaluating technology options to mitigate greenhouse gas emissions

IEAGHG Technical Report
2022-05
March 2022

Feasibility Study on Achieving Deep Decarbonization in Worldwide Fertilizer Production

IEA GREENHOUSE GAS R&D PROGRAMME

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ACHIEVING DEEP DECARBONISATION IN THE GLOBAL FERTILIZER PRODUCTION

KEY MESSAGES

This study investigated the life-cycle environmental footprint of nitrogen fertiliser production, with and without CO_2 capture, in four different regions: the United Kingdom; Norway; Saudi Arabia; and the United States. The goal was to demonstrate how deep decarbonisation of fertiliser production could be achieved in each of these regions and compare the differences between them.

- Fertiliser production is an important element in the global food production chain and is key to securing sustenance for the growing global population. This is expected to increase to 10 billion by 2050[1] and consequently fertiliser production, which currently accounts for about 1.5% of global greenhouse gas emissions[2], will continue to be essential.

- LCA (life cycle assessment) results from this study demonstrated a reduction of more than 30% in the environmental impact (as defined by the LCA) across each of the regions by integrating carbon capture technology (Scenario 2) compared to the case with no capture (Scenario 1). Norway achieved a 70% reduction in the environmental impact against the benchmark scenario.

- Steam Methane Reforming (SMR) is the most established hydrogen production technology and accounts for nearly 60% of the world's hydrogen demand. The second largest source for hydrogen currently is coal gasification at 19%.[3] Approximately 30% of the global hydrogen produced (104 Mt) is utilised for ammonia production (the chemical precursor to nitrogen fertilisers).

- Case 3, hybrid (natural gas/water electrolysis), showed the highest environmental impact unless the energy utilized for electrolysis was derived from non-fossil sources. Norway was thus found to be the regional location that delivered the least impact in ammonia synthesis due to the country's significant renewable energy electricity supply.

- For Case 3, the study found that GHG emissions/tonne of urea and UAN (urea ammonium nitrate) were substantially higher for Saudi Arabia than for the other countries examined. This was because:
    - Virtually all the Kingdom's electricity is generated from natural gas, diesel oil, crude oil, and heavy fuel oil, with minimal contribution from renewable energy technologies.
    - The study assumes the water used for electrolysis comes from desalination, which as well as being costly, is a very energy intensive process.

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[1] National Geographic. How to feed the world without destroying the planet. 2019.

[2] International Fertiliser Association. Estimating & Reporting Fertilizer-Related Greenhouse Gas Emissions. 2018

[3] International Energy Agency (IEA) Global Hydrogen Review 2021.

BACKGROUND

Nitrogen based fertiliser production is fundamental to meeting the growing food demand for the anticipated global population of 10 billion people by 2050.

The primary raw material for nitrogen production is natural gas but it can also be produced from coal, fuel oil and naphtha. The technology for synthesizing ammonia, the feedstock for nitrogen fertiliser, is based on the 100-year-old Haber-Bosch process. Approximately 65% of the natural gas utilised in Haber-Bosch process is needed as a source of hydrogen for ammonia and the remaining 35% is employed for heating the process itself.[4] China currently accounts for 95% of global ammonia capacity based on coal feedstock. In view of China's ample coal reserves, coal gasification technologies are now used extensively.

Consequently, contemporary fertiliser production is responsible for carbon emissions of up to 400 Mt/year and a projected 550 Mt/year by 2050. Without abatement technology these emissions are not sustainable if global CO_2 reduction targets are to be met. Comparatively few operational fertiliser plants include CO_2 capture. There are, for example, four commercial scale fertiliser production plants in North America where CO_2 capture is employed (three in operation and one in advanced development). Collectively they capture 3.45 Mt/year of CO_2 which is sold into commercial markets.[5] The cumulative CO_2 captured from these CCS-abated plants translates to less than 1% of the CO_2 emitted into the atmosphere from fertiliser production plants worldwide.[3]

While SMR is the main route for hydrogen production, emerging technologies that include partial oxidation (POX) and auto thermal reformation (ATR) to produce hydrogen, can potentially be beneficial for CO_2 capture because of the thermodynamically favourable conditions created by its high partial pressure in the flue gas. In the longer term, the falling cost of renewable electricity is expected to make electrolytic hydrogen competitive. Potentially, this option can also make hydrogen production from electrified SMR process economically viable.

SCOPE OF STUDY

This study was initiated with the aim of demonstrating how deep decarbonisation in fertiliser production can be achieved in regions such as Europe, the Middle East and North America. The outcome will provide comparative information on the environmental footprint of low carbon nitrogen-based fertiliser production in these jurisdictions.

The first section of the study summarises the general plant design criteria and assumptions used as a common basis for design of the fertiliser plant with and without CO_2 capture, and with electrolytic cells. The hypothetical ammonia plant is designed to produce 2,000 tonne/day of anhydrous ammonia. All the ammonia is used as feedstock for the urea, nitric acid (NA) and ammonium nitrate (AN) plants with the final products being urea and UAN (urea ammonium nitrate). The second section defines the goal and scope of the LCA. A cradle-to-gate approach was employed in this study. The boundaries of the LCA applied in this study are depicted in Figure 1. Generic datasets were used for modelling materials and chemicals, whilst the supply of energy (electricity and natural gas) and water, used specific datasets for each investigated location (i.e., UK, Norway, USA, Saudi Arabia). The environmental analysis was carried out in compliance with the International Reference Life Cycle Data

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[4] European Commission. Fertiliser in the EU. 2019.

[5] GCCSI. CCS accelerating to net zero. 2021.

System (ILCD)[6]. Sixteen impact categories including acidification, eutrophication, fossil fuel and resource depletion as well as climate change impact were included in the LCA.

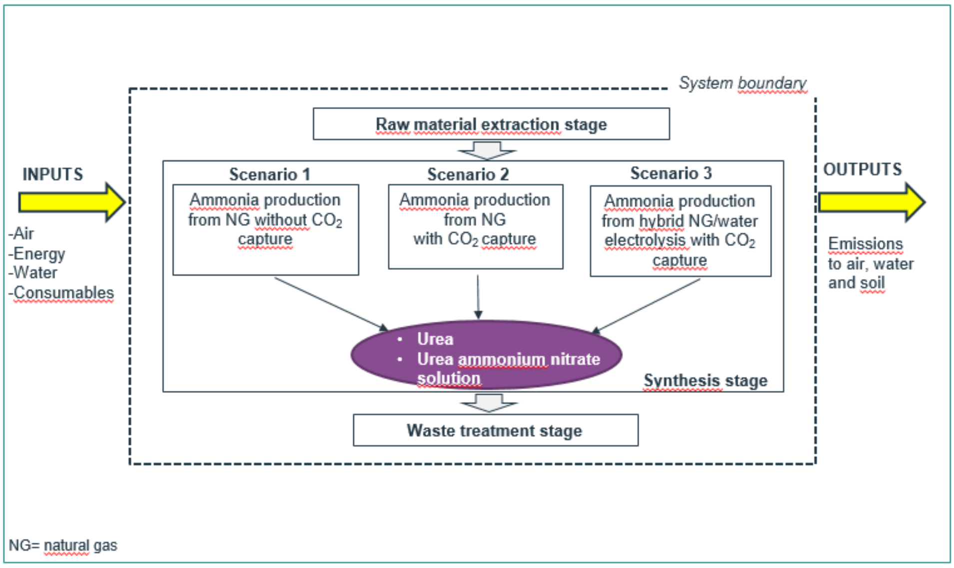

Figure 1 System boundaries for the LCA analysis

FINDINGS

A number of commercially available technologies are employed in the production of ammonia, urea, nitric acid and ammonium nitrate. However, a generic scheme for fertiliser production is employed in this study, which is applied to all four regional locations for comparative purposes. Process descriptions of the three cases studied are provided in Figures 2 to Figure 4.

For Case 1, i.e., the benchmark case of fertiliser production without CO_2 capture, ammonia is produced via nitrogen fixation where atmospheric nitrogen is converted to ammonia by reaction with hydrogen. Urea and UAN are derived from the chemical processes described in Figure 2 and the LCA results for climate change category (i.e., with incorporated CO_2 capture) for Scenario 1 is presented in Figure 3. All the results for each location, including Case 1 are presented in Table 1.

	GHG emissions per tonne of Urea [kg CO_2 eq/tonne Urea]			GHG emissions per tonne of UAN [kg CO_2 eq/tonne UAN]		
	Case 1	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
UK	473	214	814	457	213	802
Norway	383	111	108	402	144	140
USA	634	383	1,269	604	371	1,231
Saudi Arabia	686	453	2,138	639	424	2,045

Table 1 GHG emissions per tonne of product for the 3 cases

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[6] European Commission. ILCD International Life Cycle Data system

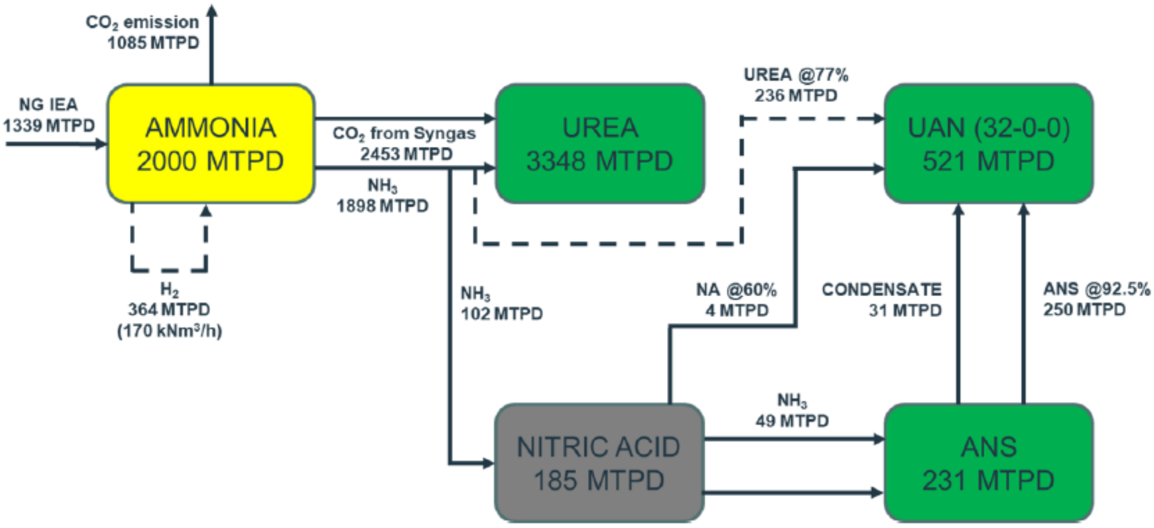

Figure 2. Fertiliser production route without CO_2 capture

For Case 2, the plant's process configuration is the same as Case 1, the difference being the CO_2 capture unit is retrofitted to the exhaust gas section of the SMR process as presented in Figure 2 and the LCA results for climate change category for Case 2 are presented in Table 1.

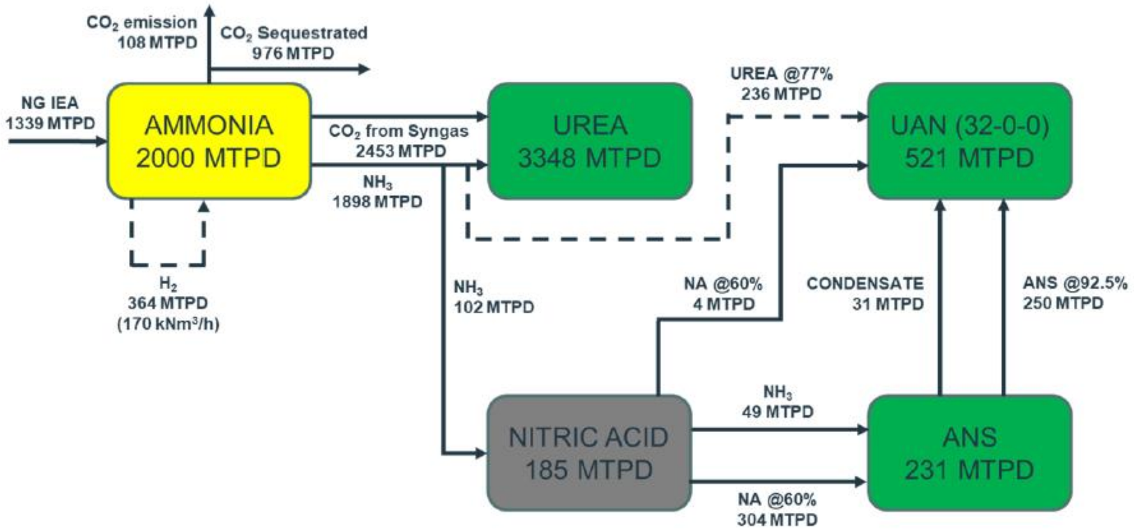

Figure 3. Fertiliser production route with CO_2 capture

For Case 3, the processes criteria downstream of the ammonia synthesis is same as Case 2. However, Case 3 represents a hybrid scenario where part of the hydrogen is supplied via water electrolysis and all the CO_2 captured from the SMR and syngas is fed to the urea synthesis plant (Figure 3) and the LCA results for climate change category for Case 3 presented in Table 1.

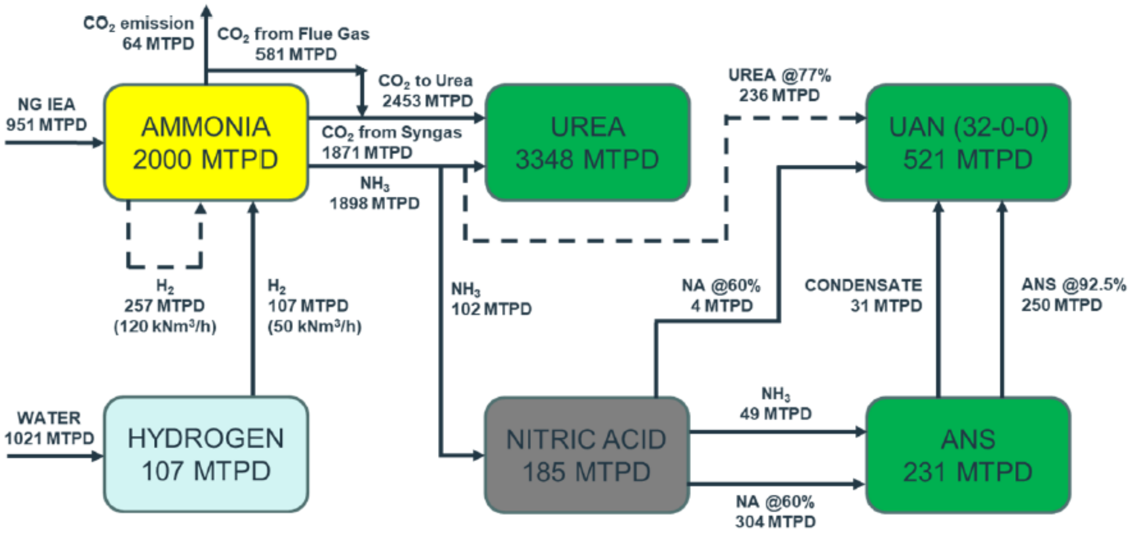

Figure 4. Hybrid fertilizer production route

The performances of the plants described above, and across the four different regions, was observed to be similar with the exception of Saudi Arabia, which takes into account the energy utilised for seawater desalination. The higher energy demand for CO_2 dehydration and compression in Case 2 makes the energy consumption higher than for Case 1. Case 3 was observed to be significantly higher in terms of energy consumption than either Case 1 or Case 2 for all locations due to the energy demand for electrolysis of water. The case for Saudi Arabia requires an even higher energy demand to provide fresh water prior to electrolysis.

The environmental perspective of each technology, in this study, is based on the LCA of their CO_2 emissions related to the production of fertiliser. The results of the LCA obtained for the selected system boundaries refers to one metric tonne of Urea and UAN solution produced. The environmental impacts from the three case studies are influenced from natural gas, electricity and water sources and hydrogen production technology (only for Scenario 3). Thus, the differences in the environmental impact results emanate from these parameters.

The LCA results showed that for all investigated regions, the integration of CCS technology (i.e., Case 2) in the ammonia synthesis route gives the highest environmental benefits when compared to the conventional ammonia synthesis route (i.e., base case), with a range between 30% and 70% reduction in burdens on climate change category. This result is mainly due to the decrease of direct CO_2 emissions from the ammonia process derived from CO_2 capture system. Although Case 2 has been established to have the lowest values in climate change category, the rest of the fifteen environmental impact categories considered in this study (e.g., water resource depletion) do not follow the same trend.

Case 2 performs slightly worst (i.e., up to 15%) compared with conventional case (Case 1) for water resource depletion category. This is mainly as a result of the additional plant consumptions to capture and sequestrate CO_2. Increase for water resources depletion also arises from higher sea/lake water consumption utilised to undertake the inter-refrigeration cooling duty of CO_2 compressors. In Case 3, unless the electricity necessary for electrolysis is obtained from non-fossil sources (e.g., Norway case) it results in the highest environmental impacts. This is particularly evident from Case 3 for the USA and Saudi Arabia. The highest value is obtained in Scenario 3 (1,269 kg CO_2 eq/tonne urea for the USA and 2,137 kg CO_2 eq/tonne urea for Saudi Arabia) and this is driven by the electricity production necessary for electrolysis.

EXPERT REVIEW COMMENTS

A review was undertaken by experts. The main comments are as follows:

- One reviewer alluded to the fact that most CO_2 is released after fertiliser application and thus does not reflect the concept of deep decarbonisation expressed in the report. This observation has been included in the report, but the aim of the study was to focus on carbon emissions produced from nitrogen fertiliser manufacturing processes. The same reviewer also stated that it would have been better to anchor this study on various electricity generation profiles as opposed to country-based to avoid the study running out of date. Hydrogen production from water electrolysis was embarked on in countries with electricity generated from predominantly fossil fuel utilisation, low carbon hydrogen from fossil fuel using CCS only should have been considered in these cases as opposed to electrolysing water with fossil fuel energy. The reviewer further stated that nitrous oxide (a greenhouse gas) should have been discussed in a nitrogen-based fertiliser production study.
- Improvements to the block flow diagram (BFD) were suggested to enhance the process description. Some information required referencing.
- A concise concluding section with diagrams and or tables communicates the deductions of the main findings efficiently instead of long text according to one of the reviewers. The reviewer further mentioned that a reflection of the environmental impacts with the changing energy landscape should have been discussed in light of the global drive towards deployment of sustainable forms of energy.
- Another reviewer suggested that a summary of the main energy benefits of the results of the different locations so be included. The reviewer also cautioned on the use of Life Cycle Inventory (LCI) in the Life Cycle Assessment (LCA) because the data are often derived from plants sampled, usually in Europe, and may not necessarily be representative of other locations.

CONCLUSIONS

The agriculture sector is projected to play an important role in achieving global climate goals. This sector is responsible for 10 to 12% of global carbon emissions. This is likely to be higher when indirect emissions from agricultural related activities are taken into account, with ammonia production alone accounting for about 420 Mt of CO_2 emissions annually.

Of the four locations explored, Norway, a country largely supplied by renewable electricity, was established as the most favourable for ammonia production. The other locations were less favourable because of the additional fossil-fuel power demands for electrolysis and, and in the case of Saudi Arabia, because of the additional fossil-fuel power requirement for desalination.

A reduction in the overall environmental impact due to urea and UAN production of 72%, 55%, 40% and 34% was achieved in Norway, UK, US and Saudi Arabia, respectively, for Case 2 compared to the benchmark Case 1. This is largely due to the reduction of CO_2 emissions from the SMR plant with the integrated CO_2 capture capability. The Urea and UAN produced in Saudi Arabia gave the highest environmental impacts followed by the US and UK. In contrast, the results place Norway in the lowest environmental impacts across all environmental impact categories. These findings are explained by the fact that the share of renewables in Norway electricity mix is higher than 90%, while the share of renewables in the electricity mix is lower for the other countries studied, approximately 25% (United Kingdom), 17% (United States), 1% (Saudi Arabia) at the time of this reporting.

Energy production (in form of electricity and natural gas) is the primary driver of the environmental impact of fertiliser production. The overall environmental impact of nitrogen fertilizer production can be reduced by implementing a more sustainable production alternative, for ammonia production. Thus, regions with abundant hydropower, or other renewable resources such as Norway, are promising choices for siting CCS technologies or electrolysers.

Recommendations for future work

- In light of the commitments of a net zero economy by 2050, techno-economic evaluation of net zero emission nitrogen-based fertiliser plant is vital to be examined. This proposed study will be based on a portfolio of the state-of-the-art low carbon and renewable energy technologies and further assess the regional influences on emerging and mature technological pathways for the net zero fertiliser plant.

- Future studies should appraise the economic viability of employing of negative emission technologies (NETs) to offset the CO_2 released from urea fertiliser application and the fertiliser production. This will also include considering the carbon footprint of fertiliser based on the mode of transport and distance transported for end usage.

- The concept of a circular carbon economy (sustainable carbon resource management) affords a value to CO_2 and consequently adds value to capturing CO_2. Commercial fertiliser plants should be studied in synergy with a possible close-to-site CO_2 utilisation project.

- The review of ammonia production technologies shows that current processes are either multistage, energy or carbon intensive, or demand considerable amounts of water resources to work. A knowledge gap thus exists to explore sustainable pathways for ammonia production.

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Acronyms

(a)MDEA	(activated) Methyl Di-Ethanol Amine
AN	Ammoniun Nitrate (plant)
ANS	Ammonium Nitrate Solution (plant)
ASU	Air Separation Unit
ATR	Auto-Thermal Reforming
B.L.	Battery Limits
BAT	Best Available Techniques
BFD	Block Flow Diagram
BFW	Boiler Feed Water
BHP	Brake Horse-Power
BoD	Bases of Design
BoP	Balance of Plant
CCS	Carbon Capture and Storage (or Sequestration)
CCUS	Carbon Capture, Utilization and Storage
CFC	Chlorofluorocarbons
CTUe	Chemistry/Toxicology Unit (ecosystem)
CTUh	Chemistry/Toxicology Unit (human)
CU	CO_2 utilisation
CW	Cooling Water
DMW	Demi Water
ECHA	European Chemicals Agency
EF	Environmental Footprint
ENCAP	Enhanced Capture of CO2
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
FU	Functional Unit
HCFC	Hydrochlorofluorocarbons
HHV	Higher Heating Value
HP	High Pressure
HTS	High Temperature Shift
ILCD	International Reference Life Cycle Data System
kBq	Kilobecquerel
LCA	Life Cicle Assessment
LCI	Life Cicle Inventory

LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LP	Low Pressure
LTS	Low Temperature Shift
MMP	Minimum Miscibility Pressure
MP	Medium Pressure
MTPD	Metric Tonnes Per Day
NA	Nitric Acid (plant)
NG	Natural Gas
NMVOCs	Non-Methane Volatile Organic Compounds
NNF	Normally No-Flow
PEF	Product Environmental Footprint
PEFCRs	Product Environmental Footprint Category Rules
PGM	Platinum Group Metals
PM	Particulate Matter
POX	Partial Oxydation
PSA	Pressure Swing Adsorption
Pt	Normalized and weighted results- Score
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
SMR	Steam Methane Reforming
UAN	Urea Ammonium Nitrate (plant)
VOCs	Volatile Organic Compounds

Introduction

Food production is expected to increase due to the global population growth. Fertilizers provide nutrients for crops to grow, mainly nitrogen, phosphorous, and potassium, and are key for meeting food industry demands.

Currently, the CO_2 emissions linked to fertilizer production are approximately 400 Mt/year with a predicted growth to 550 Mt/year by 2050.

The application of carbon capture on the production of fertilizer is recognized as one of the least-cost methods of capturing carbon dioxide from a thermodynamic and process perspective; and is equally attractive as it also has one of the lowest cost impacts on the price of the commodity. Currently, three fertilizer plants in North America capture the CO_2 and export it for enhanced oil recovery (EOR).

Ammonia, nitric acid, sulphuric acid, and phosphoric acid are the main raw chemicals used to produce fertilizers, and the first two are the main raw materials responsible for CO_2 emissions. Furthermore, the majority of fertilizer consumed are Nitrogen-based, as shown in the chart reported below, in which fertilizer consumption is broken down by base nutrients and regions in 2018.

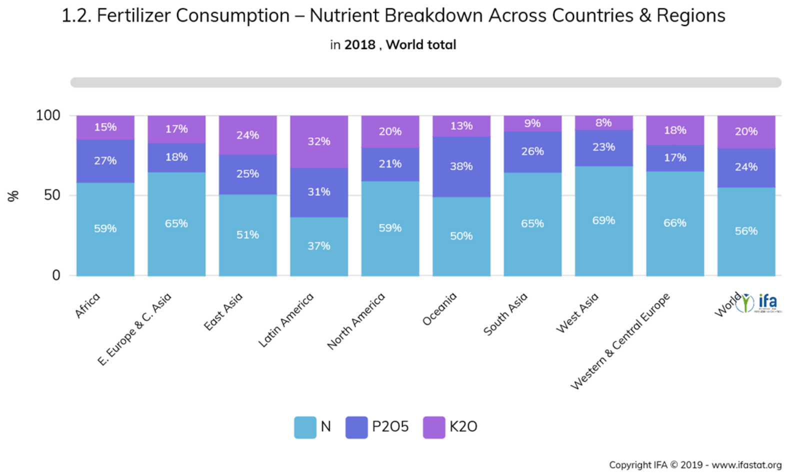

Figure 1: Fertilizer consumption breakdown across Countries & Regions[1]

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[1] International Fertilizer Association, (www.ifastat.org/databases/graph/1_2) , 03/2021

Therefore, the present study focuses only on Nitrogen Fertilizers.

The distribution of Nitrogen Fertilizers supply and demand in the world in 2019 is illustrated in the following chart.

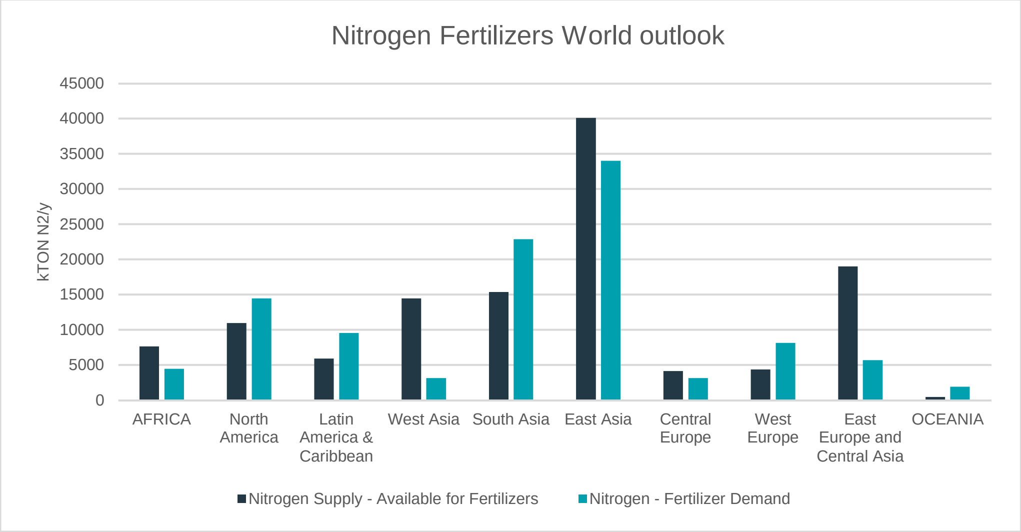

Figure 2: Distribution of Nitrogen Fertilizers supply and Demand for 2019[2]

For the production of each chemical, different routes can be employed. For example, the steam methane reforming (SMR) process is the dominating H_2 production route for ammonia production. Alternative H_2 production technologies, such as partial oxidation (POX), auto-thermal reforming (ATR), and gasification, emit a gas richer in CO_2, that would be more beneficial with regards to the implementation of carbon capture processes.

The GCCSI[3] has estimated that the application of carbon capture to fertilizer production has a cost of CO_2 avoided of $23-26/tonne CO_2. The cost of capturing the CO_2 only increases the cost of fertilizer production by 3-4% (assuming a price range of $400-450/tonne for the

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[2] FAO. 2019. *World fertilizers trends and outlook to 2022*. Rome.

[3] Global Costs Of Carbon Capture And Storage – 2017 Update, June 2017:

http://hub.globalccsinstitute.com/sites/default/files/publications/201688/global-ccs-cost-updatev4.pdf fertilizer). This places fertilizer production, with natural gas processing and bio-ethanol, among the best candidates for increasing carbon capture penetration worldwide.

However, as is equally recognized by the CCUS (*Carbon Capture, Utilization and Storage*) community, if the fertilizer produced is carbon based, as is the case with urea, a significant quantity of the carbon dioxide is expected to be released within days (Bhogal et al 2003)[4] with some studies showing greater than 96% of the carbon released as CO_2 within 8 days[5], making it impossible to reach deep emissions reduction. Hence when compared to the life cycle of other fertilizer chemistry, for example ammonium nitrate, the question that arises is which form of fertilizer, and production method, should be the focus of achieving the deepest decarbonisation of future fertilizer production.

IEAGHG has published in the past techno-economic assessments of CCS systems applied to the hydrogen, ammonia, and urea production, mainly focused on the SMR process. However, what has not been still explored is the complete fertilizer production processes with CO_2 capture from a life-cycle-assessment perspective that evaluates the net value of each production and mitigation pathway.

The objectives of this study are:

- To provide an overview of fertilizers' production processes with and without CO_2 capture;
- To assess the identified fertilizers' production processes from a whole environmental perspective;
- To analyse the results and provide recommendations on decarbonising the fertilizers' production as function of the selected regions.

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[4] Anne Bhogal, Peter Dampney and Keith Goulding, 2003. Evaluation of urea-based nitrogen fertilisers, Report for Defra Projects NT2601 and NT2602. http://sciencesearch.defra.gov.uk/Document.aspx?Document=NT2602_4057_FRP.doc

[5] Yara Research Center Hanninghof, 2016. CO_2 emission after Urea application. Available on: https://ammoniaindustry.com/wp-content/uploads/2016/04/CO2-emissions-during-urea-hydrolysis.pdf

Key Messages

- Ammonia/Urea production is one of the pillars of the basic chemicals industry worldwide. Ammonia/Urea is an important commodity used in the agriculture (fertiliser) and food industry. It is estimated that ammonia production is responsible for about 420 million tonnes of CO_2 emissions, over 1% of global energy-related CO_2 emissions.

- The IEA Greenhouse Gas R&D Programme (IEAGHG) has published techno-economic assessments of CO_2 Capture and Storage (CCS) systems applied to the hydrogen, ammonia, and urea production, mainly focused on the Steam Methane Reformer (SMR) process. However, what has not been still explored is the complete fertilizer production processes with CO_2 capture from a life-cycle-assessment perspective that evaluates the net value of each production and mitigation pathway.

- The present study considered the life-cycle emissions of nitrogen fertilizers' production using countries that are representative of certain regional conditions. The aim is to demonstrate how deep decarbonization of fertilizers' production can be achieved for regions such as Europe, North America, and Middle East. The sustainability performances in four different countries (United Kingdom, Norway, United States, Saudi Arabia) are compared, in order to see how the energy supplier affects the environmental profile of fertilizers.

- Three ammonia production routes for Urea and UAN 32.0.0 fertilizers are analysed and compared:
    - Case 1) production of ammonia from natural gas without CO_2 capture from SMR flue gases (base case);
    - Case 2) production of ammonia from natural gas with CO_2 capture from SMR flue gases;
    - Case 3) "hybrid" production of ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases.

- Plant configuration is the same for all locations, except for Saudi Arabia, in which a sea water desalination plant has been foreseen.

- For Case 1, syngas is produced from Steam Methane Reforming (SMR) followed by an air blown Auto Thermal Reformer (ATR). Hence, the syngas produced passes through High and Low Temperature Shift reactors, bulk CO_2 removal unit, methanation unit and is sent to the Ammonia Synthesis plant.

  Ammonia synthesis takes place in the Ammonia Synthesis converter. The product gas is refrigerated to condense the ammonia, which is sent to the Urea and Nitric Acid plants.

  Urea plant mainly consists of synthesis reactor, stripper, carbamate condenser, decomposer, vacuum concentrator, evaporator, and granulation plant. Some of the Urea solution is sent to the UAN plant before being dehydrated.

  Nitric Acid plant includes a reactor where a stream of ammonia is oxidized with air, a heat recovery section, and a column where oxidized stream is absorbed in water to obtain the acid.

  Ammonium Nitrate is produced by reacting Nitric Acid with Ammonia in a Neutralizer reactor and concentrating the product to the desired level. In the present study all the Ammonium Nitrate is used for UAN production, and no granulated product is foreseen.

  UAN is obtained by simply mixing Urea Solution with Ammonium Nitrate Solution and water.

- Case 2 only differs from Case 1 in the flue gas section of the SMR, where CO_2 capture and compression units are introduced.

- In Case 3 the plant configuration downstream Ammonia Synthesis is equivalent to the previous two cases, while a portion of the Hydrogen feed is provided by water electrolysis, and all the CO_2 captured from Syngas and SMR flue gases is fed to the Urea synthesis plant.

- Fertilizers production routes for each case are shown below (quantities are in Metric Tonnes Per Day).

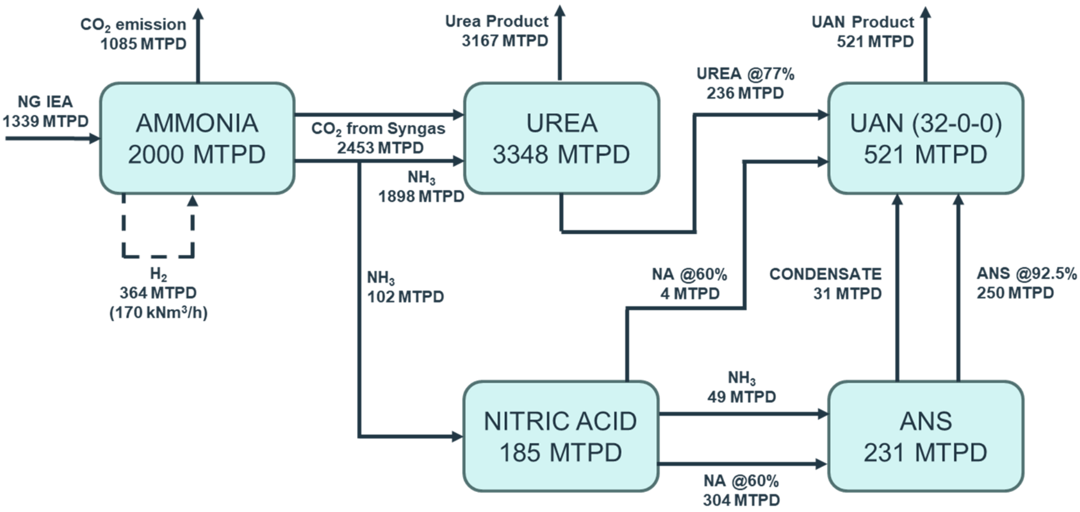

Figure 3: Fertilizers production route for Case 1

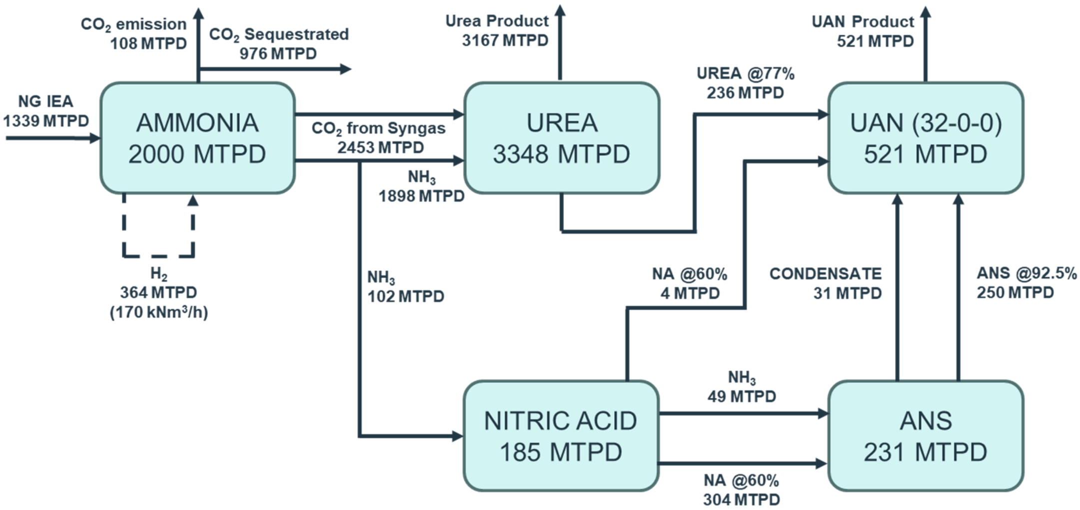

Figure 4: Fertilizers production route for Case 2

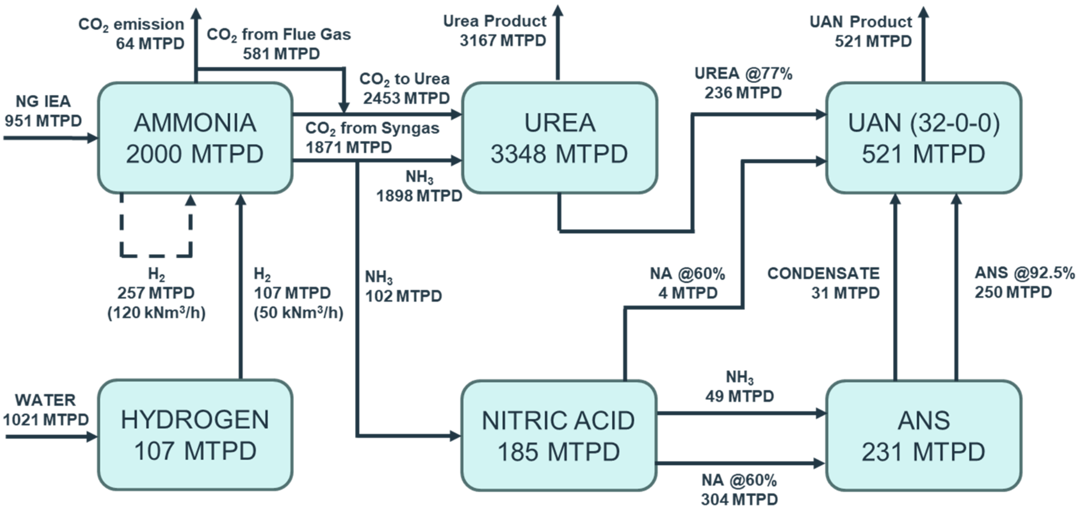

Figure 5: Fertilizers production route for Case 3

- In the following tables, Plant performance are shown for each case and region.

  It can be observed that plant performances are similar for all the considered regions, and slight variations are mainly due to lower energy demand in compression stages and higher output from condensing steam turbines in colder climates. In addition, Saudi Arabia energy demand is aggravated by the presence of the desalination unit.

  Case 2 has a higher energy demand than Case 1, mainly because of the power absorbed by the CO_2 compression unit.

  Case 3 energy demand is considerably larger than the previous two cases and is driven by the electrolysis unit electricity demand.

Plant Performance Data				
UK		**Natural Gas case without CCS**	**Natural Gas case with CCS**	**Hybrid Natural Gas/Electrolysis case with CCS**
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-18.67	-19.69	-18.84
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-6.60	-6.60	-6.60
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.23	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	34.21	39.47	300.45
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**

Table 1: Plant performance evaluated for UK

Plant Performance Data				
Norway		Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-18.52	-19.55	-18.69
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-6.60	-6.60	-6.60
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.22	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	34.06	39.32	300.31
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**

Table 2: Plant performance evaluated for Norway

Plant Performance Data				
US		**Natural Gas case without CCS**	**Natural Gas case with CCS**	**Hybrid Natural Gas/Electrolysis case with CCS**
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-18.71	-19.74	-18.88
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-6.60	-6.60	-6.60
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.27	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	34.26	39.56	300.50
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**

Table 3: Plant performance evaluated for US

Plant Performance Data				
Middle East		**Natural Gas case without CCS**	**Natural Gas case with CCS**	**Hybrid Natural Gas/Electrolysis case with CCS**
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-19.43	-20.45	-19.61
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-8.24	-8.20	-8.45
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.40	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	36.61	42.01	303.07
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**

Table 4: Plant performance evaluated for Middle East

- Mass and energy balances from process flow modelling are used as inputs for the environmental evaluation using Life Cycle Assessment (LCA) tool. Sixteen impact categories (e.g. climate change, acidification, eutrophication, fossil fuel depletion and resource depletion) are investigated, with a special focus on climate change. Moreover, the most critical stages from an environmental point of view (hotspots) were identified and alternatives were proposed in order to reduce the impact and improve the environmental and energy profiles.

- The LCA results showed that for all investigated regions, the integration of CCS technology (i.e. Case 2) in the ammonia synthesis route gives the highest environmental benefits when compared to the conventional ammonia synthesis route (i.e. base case), with a range between 30% and 70% reduction in burdens on climate change category. This result is mainly due to the decrease of direct CO_2 emissions from the ammonia process derived from CO_2 capture system. The rest of the environmental impact categories do not follow the same trend. Case 2 performs slightly worst if compared with Case 1 given that in the Case 2 the electrical consumption is higher than Case 1 due to the power absorbed by the CO_2 capture and compression plant. In Case 3, unless the electricity necessary for electrolysis is obtained from non-fossil sources (e.g. Norway case) it results in the highest environmental impacts, with contribution between 20-80% all across impact categories.

- The estimated greenhouse gas emissions (GHG) of Urea and UAN production were calculated as:

	GHG emissions per tonne of Urea [kg CO_2 eq/tonne Urea]			**GHG emissions per tonne of UAN [kg CO_2 eq/tonne UAN]**		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
UK	473	214	814	457	213	802
Norway	383	111	108	402	144	140
US	634	383	1269	604	371	1231
Saudi Arabia	686	453	2138	639	424	2045

Table 5: Estimated GHG emissions of Urea and UAN production

- Energy production (in form of electricity and natural gas) is found to be the main hotspot of fertilizers' production. This study suggests that by transitioning to low-carbon and renewable energy and implementing a more sustainable production alternative, instead of the conventional Steam Reforming technology, for ammonia production, the overall environmental burden of the nitrogen fertilizers can be reduced. Thus, areas with abundant hydropower resources such as Norway are possible choices for siting CCS technologies or electrolysers.

Feasibility Study Report Content

The following deliverables were developed during the Feasibility Study and have been included in this Report:

1. Bases of Design
2. Task 1
    - 2.1. Overall BFD
    - 2.2. Heat and Material Balance
    - 2.3. Process Description
    - 2.4. Plant & Environmental Performance data
    - 2.5. Preliminary Utility Consumption
3. Task 2 - Definition of Goal and Scope for Life Cycle Assessment (LCA)
4. Task 3 - LCAs (inventory, impact assessment and interpretation) of the selected production routes per region
5. Task 4 - Conclusions and overview of direct applications

1. BASES OF DESIGN

Client	:	IEAGHG
Project Name	:	Achieving Deep Decarbonization in Worldwide Fertilizer Production
Document Name	:	Bases of design
Wood contract	:	1-BD-1160A

ISSUED BY	:	N. Marzorati
CHECKED BY	:	G. Collodi – A. Fontanella
APPROVED BY	:	G. Collodi

Date	Revised Pages	Issued by	Checked by	Approved by
March 2021				

TABLE OF CONTENTS

1. General Data and Technical Assumptions

This section summarizes the general plant design criteria and assumptions used as a common basis for design of the Fertilizers plant with and without CO_2 capture, and with electrolytic cells.

1.1. Plant Location

Four different locations are evaluated: UK (England, South coast), Norway (Southwest coast), US (Midwest, Michigan lake coast), Middle East (Al-Jubayl, Saudi Arabia).
For each case it is considered that the plant is situated at a greenfield, with no major site preparation required. There will be no restrictions on plant area and no special civil works or constraints on the delivery of equipment are assumed. Rail lines, roads, fresh water supply (except for Middle East) and high voltage electricity transmission lines, high pressure natural gas pipeline are considered available at plant battery limits.

1.2. Climatic and Meteorological Data

For each location, main climatic and meteorological data are listed below. Conditions marked (*) are considered reference conditions for the plant performance evaluation.

UK

• Atmospheric pressure	101.3 kPa (*)
• Relative humidity	
o Average	80% (*)
o Maximum	95%
o Minimum	50%
• Ambient temperatures	
o Average air temperature	9°C (*)
o Maximum air temperature	30°C
o Minimum air temperature	-10°C

Norway

• Atmospheric pressure	101.3 kPa (*)
• Relative humidity	
o Average	80% (*)
o Maximum	95%
o Minimum	35%

• Ambient temperatures	
o Average air temperature	5°C (*)
o Maximum air temperature	30°C
o Minimum air temperature	-20°C

US

• Atmospheric pressure	101.3 kPa (*)
• Relative humidity	
o Average	70% (*)
o Maximum	95%
o Minimum	35%
• Ambient temperatures	
o Average air temperature	10°C (*)
o Maximum air temperature	35°C
o Minimum air temperature	-20°C

Middle East

• Atmospheric pressure	101.3 kPa (*)
• Relative humidity	
o Average	70% (*)
o Maximum	80%
o Minimum	60%
• Ambient temperatures	
o Average air temperature	27°C (*)
o Maximum air temperature	45°C
o Minimum air temperature	0°C

1.3. Key features of the fertilizers plant

1.3.1. Capacity

The ammonia plant is designed to produce 2000 t/d of anhydrous ammonia.
All the ammonia is used as feedstock for the Urea, Nitric Acid (NA) and Ammonium Nitrate (AN) plants.

The final products are Urea and Urea Ammonium Nitrate - UAN (32-0-0) solution, but it is foreseen to stock and sell intermediate products in case of upset of any unit downstream the ammonia production plant.

Three main cases are analyzed in this study for each location:

- Production of Ammonia from Natural Gas without CO_2 capture from SMR (Steam Methane Reformer) flue gases
- Production of Ammonia from Natural Gas with CO_2 capture from SMR flue gases
- Hybrid Production of Ammonia from Natural Gas and Water Electrolysis.

These cases have been proposed in line with short-medium term decarbonization plan of major Fertilizers companies.

In the following table, the overall preliminary material balance is laid out for each case:

	Natural gas case without CO_2 capture	Natural gas case with CO_2 capture	Hybrid Natural Gas/Electrolysis case
Hydrogen Production from Natural Gas	364	364	257
Hydrogen Production from Water Electrolysis	0	0	107
Ammonia Production	2000	2000	2000
Ammonia to Urea plant	1898	1898	1898
Urea production	3348	3348	3348
Urea product to B.L.	3167	3167	3167
Urea to UAN plant	236 (77% solution)	236 (77% solution)	236 (77% solution)
Ammonia to NA plant	53	53	53
NA production	185	185	185
NA to ANS plant	304 (60% solution)	304 (60% solution)	304 (60% solution)
NA to UAN plant	4 (60% solution)	4 (60% solution)	4 (60% solution)
Ammonia to ANS plant	49	49	49
ANS production	231	231	231
ANS to UAN plant	250 (92.5% solution)	250 (92.5% solution)	250 (92.5% solution)
Condensate to UAN plant	31	31	31
UAN (32-0-0) solution product to B.L.	521	521	521
Compressed CO_2 product stream to B.L.	0	976	0

All quantities in the table are expressed in metric tonnes per day (MTPD).

In the Natural Gas case with CO_2 capture and in the hybrid Natural Gas/Electrolysis case, it is foreseen to target a 90% CO_2 sequestration from SMR flue gases.
The fertilizers' production route for the Base case is represented in the drawing below:

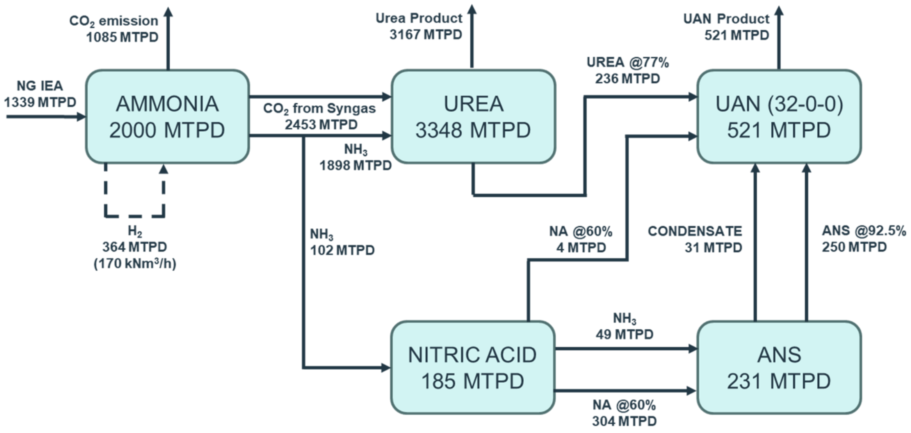

Figure 1: Base case Fertilizers' production route

The fertilizers' production route for the Natural Gas Case with CO_2 capture is represented in the drawing below:

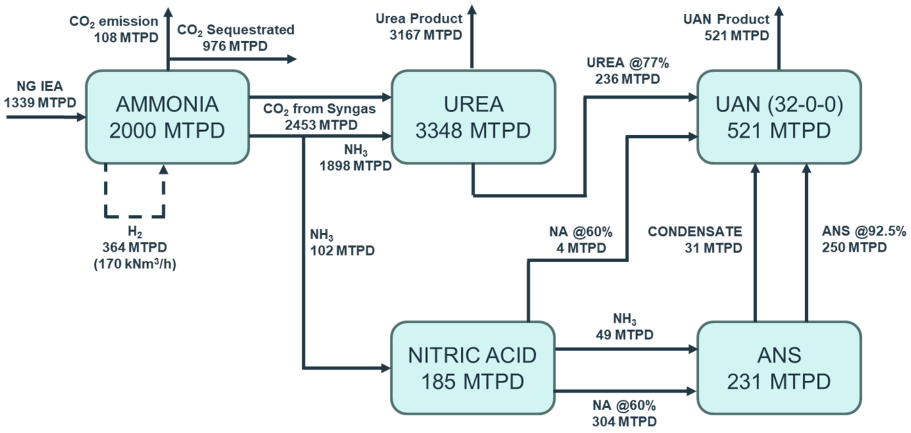

Figure 2: NG with CO_2 Capture case Fertilizers' production route

The fertilizers' production route for the Hybrid Natural Gas/Electrolysis case is represented in the drawing below:

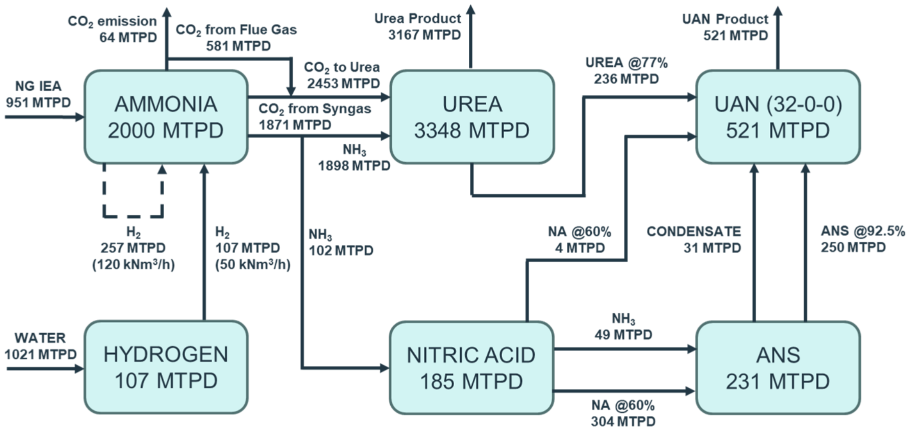

Figure 3: Hybrid NG / Electrolysis case Fertilizers' production route

1.3.2. *Configuration*

The overall production plant consists of the following units:

- Ammonia plant includes:
  - Primary reformer (Feedstock Pre-treatment, (Pre-reformer) and SMR)
  - Secondary Reformer (ATR)
  - High and Low temperature CO Shift Conversion Section
  - Bulk CO_2 Removal Section
  - Methanation
  - Ammonia Synthesis and Refrigeration
  - Ammonia Storage
  - CO_2 Capture System from SMR flue gases (only for CO_2 capture case and Electrolysis case)
  - CO_2 Compression and Dehydration (only for CO_2 capture case)
- Electrolysis plant for hydrogen production (only for Electrolysis case) includes:
  - Electrolytic cells
  - Hydrogen Purification and Compression
- Urea plant includes:
  - Urea Synthesis

  - Urea Solution Concentration
  - Granulation
  - Wastewater Treatment
- Nitric Acid plant includes:
  - NH_3 converter
  - Absorption column
- Ammonium Nitrate plant includes:
  - Neutralizer
  - Ammonium Nitrate Concentration
  - Granulation
- UAN plant includes:
  - Mixing
  - UAN tanks
- Steam and BFW plant
- Demi-Water Plant
- Sea Water Desalination Plant (only for Middle East)
- Utilities and Balance of Plant (BoP), consisting of:
  - Cooling Water System
  - Flare System
  - Interconnecting
  - Drain System
  - Buildings (control Room, Laboratories, Electrical Sub-station)

1.3.3. Plant Turndown

The minimum turndown of the Ammonia and Urea considered in this study is assumed at 40%. This should be necessary during start-up or upset within the fertilizers' production operation.

1.4. Plant's battery limits

Main plant battery limits are listed below:

- Natural gas (in)
- Raw water (in) (except for Middle East case)
- Electric power (in)
- Sea / lake water (in/out)
- Urea (out)
- UAN (out)
- Wastewater streams (out)
- Compressed CO_2 rich stream (out) (only for CO_2 capture case)

1.5. Feedstock Specification

1.5.1. Natural Gas

Natural gas is used as the main feedstock and fuel to the ammonia plant and delivered to the plant battery limits from a high pressure pipeline.

The specifications of natural gas follow IEA standards. Composition, heating value and pressure at B.L. are reported in the table below.

Natural Gas analysis (vol%)	
Methane	89.0
Ethane	7.0
Propane	1.0
Butane	0.1
Pentane	0.01
CO_2	2.0
Nitrogen	0.89
Sulphur	5 ppm_v*
Total	100.00

HHV, MJ/kg	51.473
LHV, MJ/kg	46.502

Conditions at plant B.L.	
Pressure, MPa	7.0

*5 ppm_v of H_2S are assumed to be present in the natural gas for design purposes

1.5.2. Water to Electrolysis

Demi-Water from demi-water plant is used as feedstock in electrolysis plant.
Demi-Water specification is reported under 1.9.3.

1.6. Products Specification

The products specifications of the plant are listed below.

1.6.1. Ammonia

Typical commercial specifications of anhydrous ammonia are reported below. The following specifications are also valid for the ammonia sent to the Urea, Nitric Acid and Ammonium Nitrate Plant.

Ammonia		Value	Unit
NH_3	min	99.5	wt. %
Water	max	0.5	wt. %
Oil	max	5	ppm wt.
Nitrogen	max	8	ppm wt.
CH_4	max	10	ppm wt.
H_2	max	150	ppm wt.
Argon + Helium	max	10	ppm wt.

1.6.2. Carbon Dioxide

The specifications of the CO_2 as delivered from the plant's B.L. to the pipeline are presented in the following table (valid only for the CO_2 capture case).

Maximum allowable impurities in the product CO_2 ([1])	
H_2	4% [2,3]
N_2 + Ar	4% [3,4]
O_2[5]	100 ppm [3,6]
CO	0.2% [7]
H_2S	20 ppm [5]
H_2O	50 ppm [8]

Pressure at B.L.	11 MPa
Temperature at B.L.	30°C

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[1] Based on the information available in 2012 on the requirements for CO_2 transportation and storage in saline aquifers.

[2] Hydrogen concentration to be normally lower to limit loss of energy and economic value. Further investigation is required to understand hydrogen impact on supercritical CO_2 behavior.

[3] Total non-condensable content (N_2 + O_2 + H_2 + CH_4 + Ar): maximum 4% vol. basis. This is based on the recommendations reported in the ENCAP Project (http://www.encapCO2.org).

[4] The limit on concentrations of inerts are to reduce the volume for compression, transport and storage and limit the increase in Minimum Miscibility Pressure (MMP) in Enhanced Oil Recovery (EOR).

[5] Oxygen and H_2S content should be specified in conjunction with water content to limit corrosion in the downstream infrastructure.

[6] Oxygen limit is considered tentative due to the lack of practical experience on the operation of the CO_2 storage infrastructure. It is expected that stringent limit will be in place for EOR operation.

[7] CO limits are set from a health and safety perspective.

[8] Water specification is to ensure there is no free water and hydrate formation.

1.6.3. *Urea*

Typical commercial specifications of granulated urea are listed in the following table.

Urea (Granulated)		**Value**	**Unit**
Total Nitrogen	min	46	wt. %
Free Ammonia	max	100	ppm wt.
Biuret	max	0.9	wt.%
Moisture	max	0.3	wt.%
Size distribution	Between 1&4 mm in diameter	95	wt.%

Urea sent to UAN plant is in a 77% solution with water.

1.6.4. *Nitric Acid*

Nitric acid is sent to Ammonium Nitrate plant and UAN plant in a 60% solution with water. Typical commercial specifications of nitric acid (60%) are listed in the following table.

Nitric acid (60%)		**Value**	**Unit**
Nitric Acid concentration	min	60	wt. %
Nitrous Acid	max	20	mg/kg
Chlorides	max	1	ppm wt.
Heavy metals (Cu, Cr, Ni, Fe, PGM's)	max	50	ppm wt. (total)
	max	5	ppm wt. (Fe)
	max	1	ppm wt. (Cu)

1.6.5. *Ammonium Nitrate*

Ammonium Nitrate is sent to UAN plant in a 92.5% solution with water.
Typical commercial specifications of Ammonium Nitrate Solution, valid for the ANS sent to the UAN plant, are listed in the following table.

Ammonium Nitrate (Solution)		**Value**	**Unit**
AN Solution Concentration		92.5	wt. %
Chlorides	max	10	ppm wt.
Total Organic content	max	50	ppm wt.
Heavy metals (Cu, Cr, Ni, Fe, PGM's)	max	50	ppm wt. (total)
	max	1	ppm wt. (Cu)

Typical commercial specifications of fertilizer grade, granulated Ammonium Nitrate are listed in the following table.

Ammonium Nitrate (Granulated)		Value	Unit
Total Nitrogen		26.8 – 27.2	wt. %
Moisture	max	0.17	wt. %
$NaNO_3$	min	0.8	wt. %
$Al_2(SO_4)_3$		0.7 – 0.9	wt. %
Granulation Additive		300	ppm wt.
Coating		0.6 – 0.8	$^0/_{00}$
Postconditioner	min	700	ppm wt.

1.6.6. *UAN*

UAN composition can have a nitrogen content ranging from 28 to 32 wt.%.
In this study, only the UAN grade containing 32 wt.% of nitrogen is considered.
In the following table, a typical commercial specification for UAN(32-0-0) is reported.

UAN (32-0-0)	Value	Unit
Ammonium nitrate	45	wt. %
Urea	35	wt. %
Water	20	wt. %
pH	7	

1.7. Capacity factor

The table below presents the expected capacity factor (average yearly capacity factor, including the scheduled maintenance) of the fertilizer complex.

Year	Capacity factor
1st year of operation	70%
2nd-25th year of operation	95%

1.8. Environmental Limits

The environmental limits set up for each case are outlined in this section.

1.8.1. Gaseous Emissions

Gaseous emissions discharged from the plant should comply with the standard limits required by the local directives currently in force.

In the present study the following limits have been established, in compliance with Industrial Emission Directive.

The gaseous emissions from the Ammonia plant will typically not exceed the following limits:

NO_x (as NO_2)*	≤ 120 mg/Nm^3
SO_x (as SO_2)*	**
CO	≤ 30 mg/Nm^3

*Emission expressed in mg/Nm^3 @ 3% O_2, dry basis.

**SO_x will be minimal – given that NG as supplementary fuel contains only less than 5 ppm.

The gaseous emissions from the Nitric Acid plant will typically not exceed the following limits:

NO_x	≤ 30 ppmv
N_2O	≤ 0.2 kg N_2O/t HNO_3 produced
NH_3 slip	≤ 5 ppmv

The gaseous emissions from the Solid Products plants will typically not exceed the following limits:

Particulate*	≤ 20 mg/Nm^3
Ammonia*	≤ 10 mg/Nm^3

*Emission expressed in mg/Nm^3 @ 3% O_2, dry basis.

1.8.2. Liquid Effluent Discharge

Characteristics of wastewater discharged from the plant should comply with the standard limits required by the local directives currently in force.

Sea water used in the primary cooling system is returned to the sea with allowable maximum temperature increase of 7°C.

1.8.3. Solid Wastes Disposal

Solid wastes from the Ammonia and Nitric Acid Plants consist of the spent catalyst. All solid wastes will be handled in accordance with the instructions and guidelines provided by the catalyst vendors and the plant owner's established procedure.

The spent catalyst collected from the plant are in their oxidized/inert state; as such, these are considered non-hazardous.

Nickel catalyst from reformer (and pre-reformer), and Platinum catalyst from ammonia oxidizer in the nitric acid plant can often be recovered.
The other spent catalyst would normally be disposed in the landfill.

1.8.4. Noise Pollution

All the equipment of the plant is designed to obtain a sound pressure level of 85 dB(A) at 1 meter from the equipment.

1.9. Utility and Service fluids Characteristics/Conditions

The following sections present the main utilities and service fluids used within the plant.

1.9.1. Cooling Water

The cooling water system is based on once through seawater/lake water cooling for the primary system, and close circuit demi-water cooling with cooling towers for the secondary system.

Primary System – Seawater Cooling Specification

Conditions for the primary system are specified for each of the considered locations.

UK
Source: sea water in once through system
Service: steam turbine condenser and CO_2 compression unit.
Type: clear filtered and chlorinated, without suspended solids and organic matter.
Salinity: 35 g/l

Supply temperature:

- Average supply temperature (on yearly basis):	13°C
- Max supply temperature (average summer):	16°C
- Min. supply temperature (average winter):	10°C
- Max allowable temperature increase:	7°C

Return temperature:	
- Average return temperature:	20°C
- Max return temperature:	23°C
Design temperature:	50°C
Operating pressure at condenser inlet:	0.05 MPa(g)
Design pressure:	0.4 MPa(g)
Max allowable ΔP for users:	0.05 MPa(g)
Turbine condenser minimum ΔT:	5°C
Turbine condenser conditions	
- Temperature	28°C
- Pressure	0.0038 MPa

Norway
Source: sea water in once through system
Service: steam turbine condenser and CO_2 compression unit.
Type: clear filtered and chlorinated, without suspended solids and organic matter.
Salinity: 35 g/l

Supply temperature:	
- Average supply temperature (on yearly basis):	10°C
- Max supply temperature (average summer):	15°C
- Min. supply temperature (average winter):	6°C
- Max allowable temperature increase:	7°C
Return temperature:	
- Average return temperature:	17°C
- Max return temperature:	22°C
Design temperature:	50°C
Operating pressure at condenser inlet:	0.05 MPa(g)
Design pressure:	0.4 MPa(g)
Max allowable ΔP for users:	0.05 MPa(g)
Turbine condenser minimum ΔT:	5°C
Turbine condenser conditions	
- Temperature	27°C
- Pressure	0.0036 MPa

US

Source: lake water in once through system
Service: steam turbine condenser and CO_2 compression unit.
Type: clear filtered and chlorinated, without suspended solids and organic matter.
Salinity: 0.1 g/l

Supply temperature:

- Average supply temperature (on yearly basis): 11°C
- Max supply temperature (average summer): 20°C
- Min. supply temperature (average winter): 4°C
- Max allowable temperature increase: 7°C

Return temperature:

- Average return temperature: 18°C
- Max return temperature: 27°C

Design temperature: 55°C
Operating pressure at condenser inlet: 0.05 MPa(g)
Design pressure: 0.4 MPa(g)
Max allowable ΔP for users: 0.05 MPa(g)
Turbine condenser minimum ΔT: 5°C
Turbine condenser conditions

- Temperature 32°C
- Pressure 0.0048 MPa

Middle East

Source: sea water in once through system
Service: steam turbine condenser and CO_2 compression unit.
Type: clear filtered and chlorinated, without suspended solids and organic matter.
Salinity: 45 g/l

Supply temperature:

- Average supply temperature (on yearly basis): 26°C
- Max supply temperature (average summer): 32°C
- Min. supply temperature (average winter): 20°C
- Max allowable temperature increase: 7°C

Return temperature:

- Average return temperature: 33°C
- Max return temperature: 39°C

Design temperature:	65°C
Operating pressure at condenser inlet:	0.05 MPa(g)
Design pressure:	0.4 MPa(g)
Max allowable ΔP for users:	0.05 MPa(g)
Turbine condenser minimum ΔT:	5°C
Turbine condenser conditions	
- Temperature	44°C
- Pressure	0.0091 MPa

Secondary System – Closed Circuit Demineralized Water (Demi-Water) Cooling with Cooling Towers specification

Conditions for the secondary system are specified for each of the considered locations.

UK

Source:	demineralized water stabilized & conditioned – seawater cooled
Service:	for machinery cooling and for all plant users other than steam turbine condenser and CO_2 compression exchangers

Supply temperature:

– Average supply temperature:	20°C
– Max supply temperature:	23°C
– Max allowable temperature increase:	11°C

Design temperature:	60°C
Operating pressure at Users:	0.3 MPa(g)
Design pressure:	0.7 MPa(g)
Max allowable ΔP for Users:	0.15 MPa(g)

Norway

Source:	demineralized water stabilized & conditioned – seawater cooled
Service:	for machinery cooling and for all plant users other than steam turbine condenser and CO_2 compression exchangers

Supply temperature:

– Average supply temperature:	17°C
– Max supply temperature:	22°C
– Max allowable temperature increase:	11°C

Design temperature: 60°C
Operating pressure at Users: 0.3 MPa(g)
Design pressure: 0.7 MPa(g)
Max allowable ΔP for Users: 0.15 MPa(g)

US

Source: demineralized water stabilized & conditioned – lake water cooled
Service: for machinery cooling and for all plant users other than steam turbine condenser and CO_2 compression exchangers

Supply temperature:

- Average supply temperature: 21°C
- Max supply temperature: 30°C
- Max allowable temperature increase: 11°C

Design temperature: 70°C
Operating pressure at Users: 0.3 MPa(g)
Design pressure: 0.7 MPa(g)
Max allowable ΔP for Users: 0.15 MPa(g)

Middle East

Source: demineralized water stabilized & conditioned – seawater cooled
Service: for machinery cooling and for all plant users other than steam turbine condenser and CO_2 compression exchangers

Supply temperature:

- Average supply temperature: 36°C
- Max supply temperature: 42°C
- Max allowable temperature increase: 11°C

Design temperature: 80°C
Operating pressure at Users: 0.3 MPa(g)
Design pressure: 0.7 MPa(g)
Max allowable ΔP for Users: 0.15 MPa(g)

1.9.2. *Air Cooling System*

UK, Norway
Air temperature to be considered for the air cooler design is set at 25°C.

US
Air temperature to be considered for the air cooler design is set at 30°C.

Middle East
Air temperature to be considered for the air cooler design is set at 40°C.

1.9.3. *Demineralized Water (Demi-Water)*

Type:		Treated raw water
Operating pressure at grade (min):		0.5 MPa(g)
Design pressure:		0.95 MPa(g)
Operating temperature:		Ambient
Design temperature:		50°C
Specifications:		
– pH		6.5÷7.0
– Total dissolved solids	mg/kg	0.1 max
– Conductance at 25°C	µS	0.15 max
– Iron	mg/kg as Fe	0.01 max
– Free CO_2	mg/kg as CO_2	0.01 max
– Silica	mg/kg as SiO_2	0.015 max

1.9.4. *Steam Conditions*

The conditions for the HP, MP and LP steam considered in the evaluation for the Fertilizers Complex are presented in the process description of TASK 1.

1.9.5. *Instrument and Plant Air Specifications*

Instrument Air

Operating pressure	
– Normal:	0.7 MPa(g)
– Minimum:	0.5 MPa(g)
Design pressure:	1 MPa(g)
Operating temperature (max):	40°C
Design temperature:	60°C
Dew point @ 0.7 MPa(g):	-30°C

Plant Air

Operating pressure:	0.7 MPa(g)
Design pressure:	1 MPa(g)
Operating temperature (max):	40°C
Design temperature:	60°C

1.9.6. Nitrogen

Supply pressure:	0.65 MPa(g)
Design pressure:	1.15 MPa(g)
Supply temperature (min):	15°C
Design temperature:	70°C
Min Nitrogen Purity:	99.9% vol. (instrument grade)

1.9.7. Chemicals

The chemicals used in the plant, generally consist of:

- The additives used in treating boiler feed water and condensates.
  For example:
  - Oxygen scavenger: Nalco Elimin-OX 100% or equivalent
  - Phosphate injection: Water solution with 50% Na_2HPO_4
  - pH control injection: Morpholine (100%)

Design pressure:	atmospheric pressure plus full tank liquid solution
Design temperature:	80°C

- The additives used in granulation plants.
  For example:
  - Granulation additive
  - Coating agents
  - Formaldehyde
  - Organic/Inorganic salts
  - Sulfuric acid

- Chemicals added to UAN to inhibit corrosion.

- Chemicals added in the desalination plant (Middle East case only)

1.9.8. Electric Power

Voltage and frequency of electric grid connection for each location are reported below:

UK
High voltage grid connection: 380 kV
Frequency: 50 Hz

Norway
High voltage grid connection: 380 kV
Frequency: 50 Hz

US
High voltage grid connection: 380 kV
Frequency: 60 Hz

Middle East
High voltage grid connection: 380 kV
Frequency: 60 Hz

1.10. Units of measurement

The units of measurement used in this study are taken from SI units.

1.11. Codes and Standards

The design of the process and utility units are in general accordance with the main International and Local Standard Codes.

1.12. Software Codes

For the design of the Syngas Plant, a simulation has been carried out with Aspen HYSYS v10 (by AspenTech) to evaluate the heat and material balance in the hybrid Natural Gas/Electrolysis case.

1.13. Environmental impact assessment of fertilizers' production

Carbon capture and storage (CCS) is perceived as a technology to mitigate climate change and conserve nonrenewable resources, especially in the fertilizer industry. Nevertheless, capturing CO_2 is an energy intensive process[9]. To evaluate the environmental impact of this new technology applied to the fertilizer sector a life cycle assessment (LCA) is an appropriate tool, since it takes into account all relevant impacts occurring during the entire life cycle[10]. It allows quantifying and estimating the environmental impact of products or services and in addition it is a possibility to assess environmental improvements.

A life cycle framework of the fertilizers' production will be established in this study based on the International Standards ISO 14040:2006 and ISO 14044:2018, and the analysis of material and energy flows in the production process. According to ISO standards, the LCA concept consists of four major steps: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment and (4) interpretation. The first component of an LCA is the definition of the goal and scope of the analysis. This includes the description of the analysed system and the definition of system boundaries. Furthermore, a reference unit, to which all the environmental impacts are related, has to be defined. According to the LCA terminology this reference unit is called a functional unit. The second major step is to draw up an inventory (LCI, Life Cycle Inventory) of all the resources used and all the emissions released into the environment connected with the production of fertilizer. To further interpret the data of the Life Cycle Inventory it is necessary to evaluate the environmental impact associated with emissions and resource uses. This is done in the third LCA step, the Life Cycle Impact Assessment (LCIA). Several LCIA methods have been developed and published. The ILCD 2011 Midpoint impact assessment method released by the European Commission, Joint Research Centre in 2012, has been selected to be used in this study. The default 15 Environmental Footprint impact categories as listed in the ILCD handbook 'Recommendations for LCIA in the European context' (EC-JRC, 2011)[11] such as climate change potential, acidification potential, eutrophication potential, water depletion, renewable and non-renewable resources consumption, etc., will be used in this study.

In the fourth phase of an LCA the results of the LCIA are used to identify hot-spots and possibilities of reducing the negative environmental effects of the systems under analysis.

In the present study, various resources-based ammonia generation pathways for Urea and Urea Ammonium Nitrate (UAN) fertilizer production are comparatively assessed using life cycle

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[9] Thambimuthu K, Soltanieh M, Abanades JC, Rodney A, Bolland O, Davison J, et al. 2005. Capture of CO_2. In: Metz B, Davidson O, de Coninck H, Loos M, Meyer L, editors. IPCC special report on carbon dioxide capture and storage. Cambridge: Cambridge University Press p. 105–78.

[10] Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's guide to LCA. An orientation in life cycle assessment methodology and application. In: Studentlitteratur. Holmsbergs i Malmö AB, Malmö, Sweden.

[11] European Commission, Joint Research Centre, Institute for Environment and Sustainability. Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information. First edition. February 2012. EUR 25167. Luxembourg. Publications Office of the European Union; 2012.

considerations from ‘cradle-to-gate’[12]. The system boundaries determine which unit processes are needed to be included in an LCA study. The system boundaries for the LCA analysis are defined as shown in Fig. 2, namely: raw materials extraction stage, synthesis stage and waste-treatment stage. In the raw materials extraction stage, natural resources are extracted and transported to the fertilizer manufacturing plant as raw materials. In the synthesis stage, the intermediate material ammonia is synthesized using natural gas or hybrid natural gas/water at first and then used to synthesis urea with CO_2. In the waste-treatment stage, waste gas, water, and residues are disposed of in several ways.

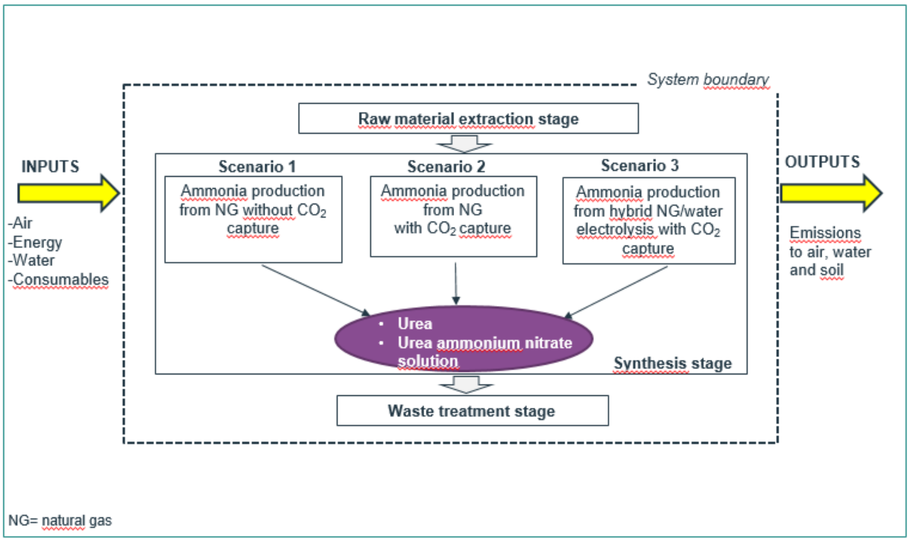

Figure 4. System boundary for the LCA analyses.

In the current study, a comparative LCA will be conducted to analyze the environmental impacts of 1 tonne of Urea and 1 tonne of Urea Ammonium Nitrate (UAN) produced with three different technologies: from natural gas with and without CO_2 capture from SMR flue gases (Case 1 and Case 2) and from hybrid natural gas/water electrolysis (Case 3).

Depending on the type of CCS technology, the consumption of electricity might contribute significantly to the environmental impacts of the product system. Since the results of LCAs on CCS systems are sensitive to the choice of electricity supplier, four regions that are representative of certain regional conditions will be considered for the LCA: United Kingdom, Norway, United States, Saudi Arabia.

The LCA studies will be conducted using SimaPro v.9.1 professional software and most updated versions of main commercial databases (i.e Ecoinvent, Agrifootprint, Agribalyse, etc.).

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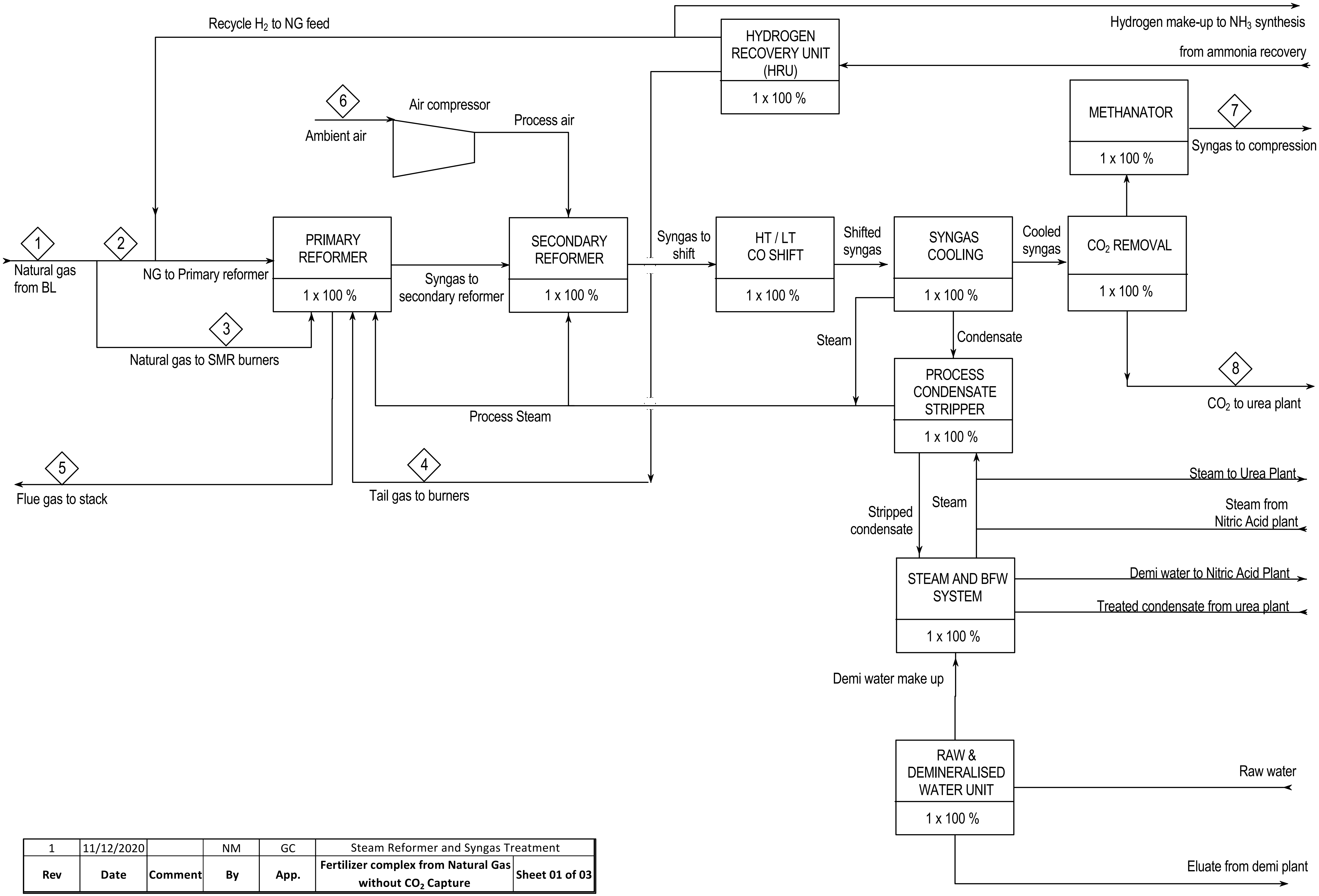
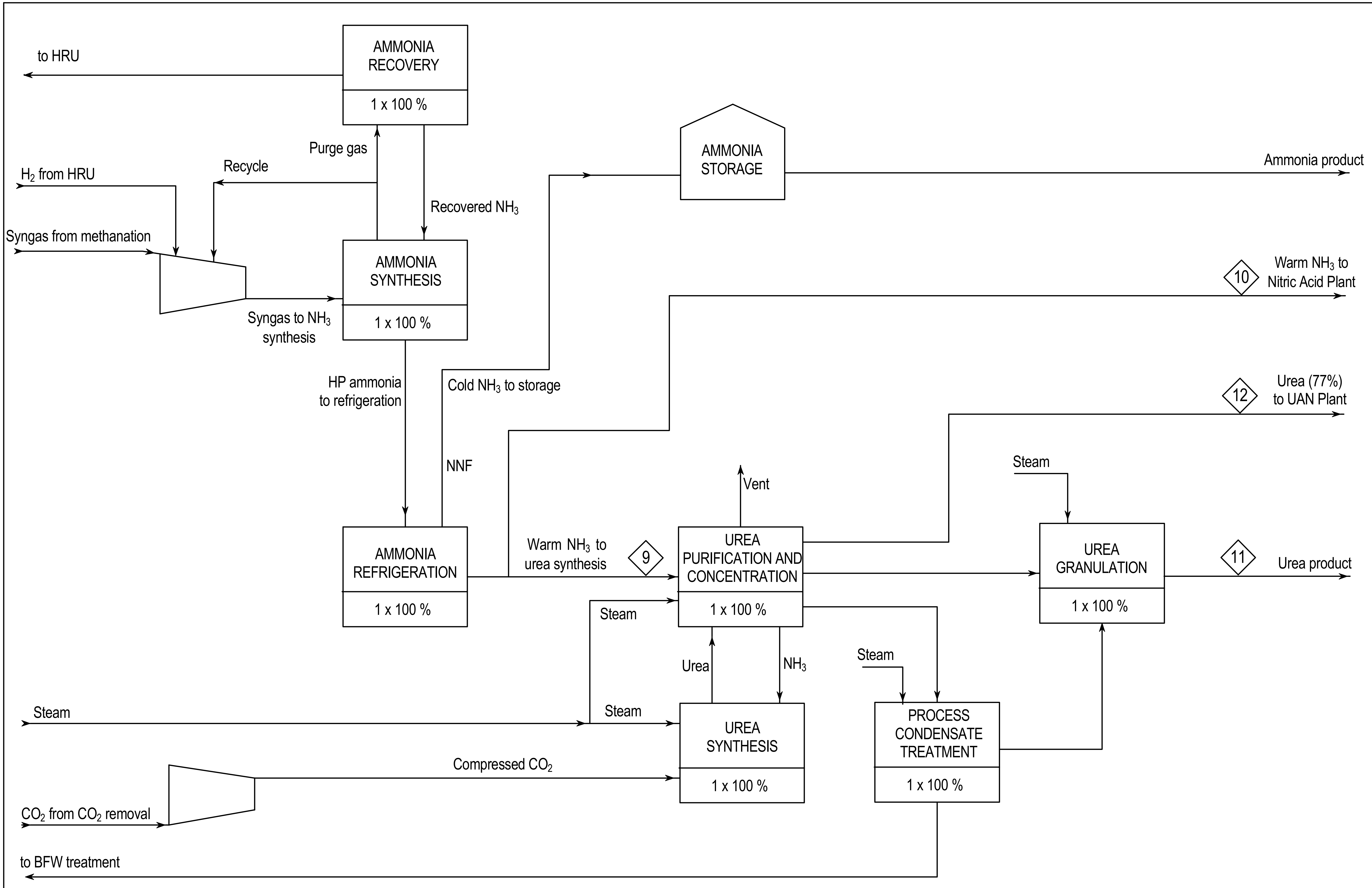
[12] Cradle-to-gate is an assessment of a partial product life cycle from resource extraction (cradle) to the factory gate (i.e., before it is transported to the consumer). The use phase and disposal phase of the product are omitted in this study.

2. TASK 1

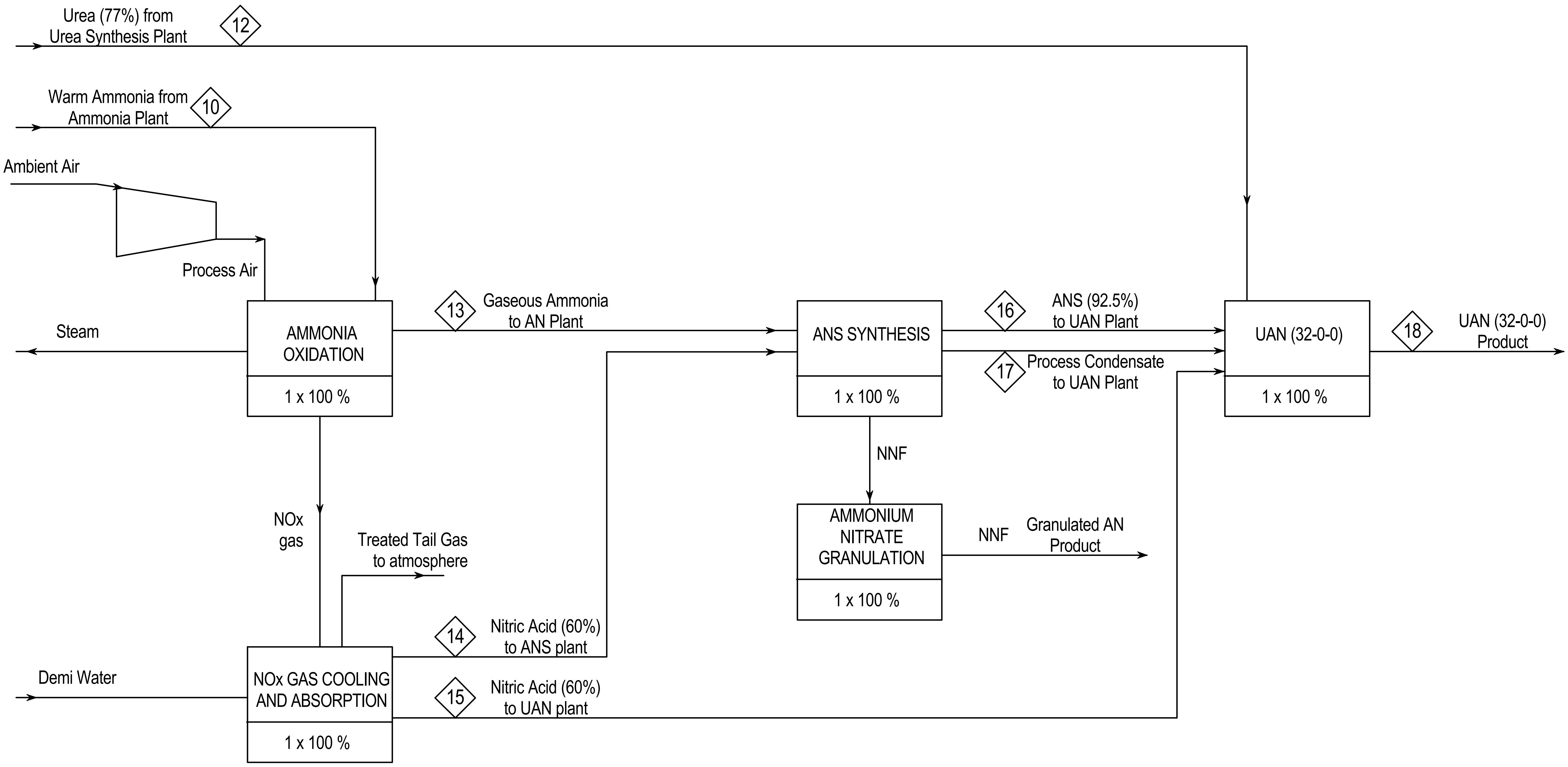
2.1 TASK 1 – OVERALL BFD



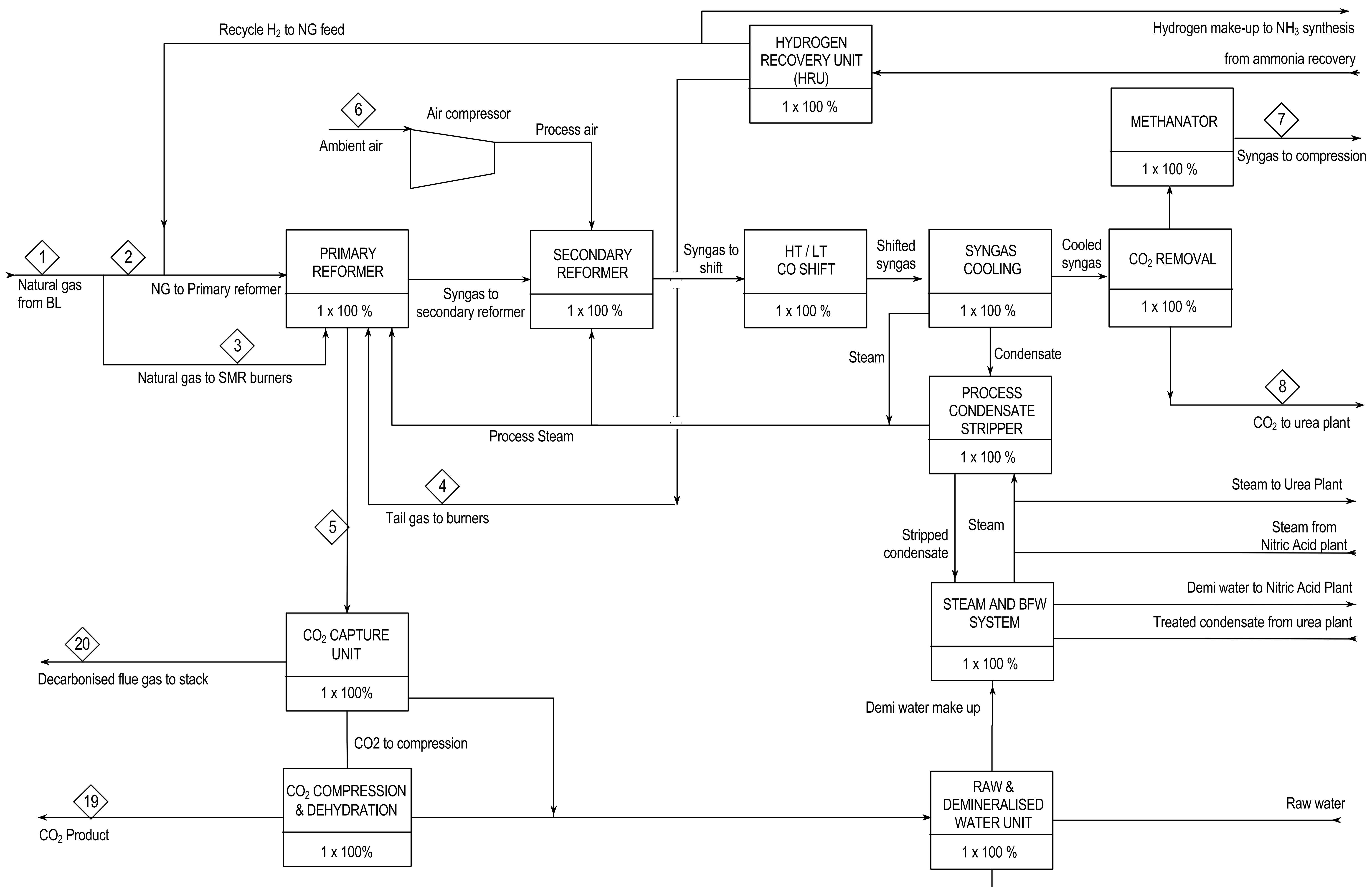
1	11/12/2020		NM	GC	Steam Reformer and Syngas Treatment	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas without CO_2 Capture**	**Sheet 01 of 03**



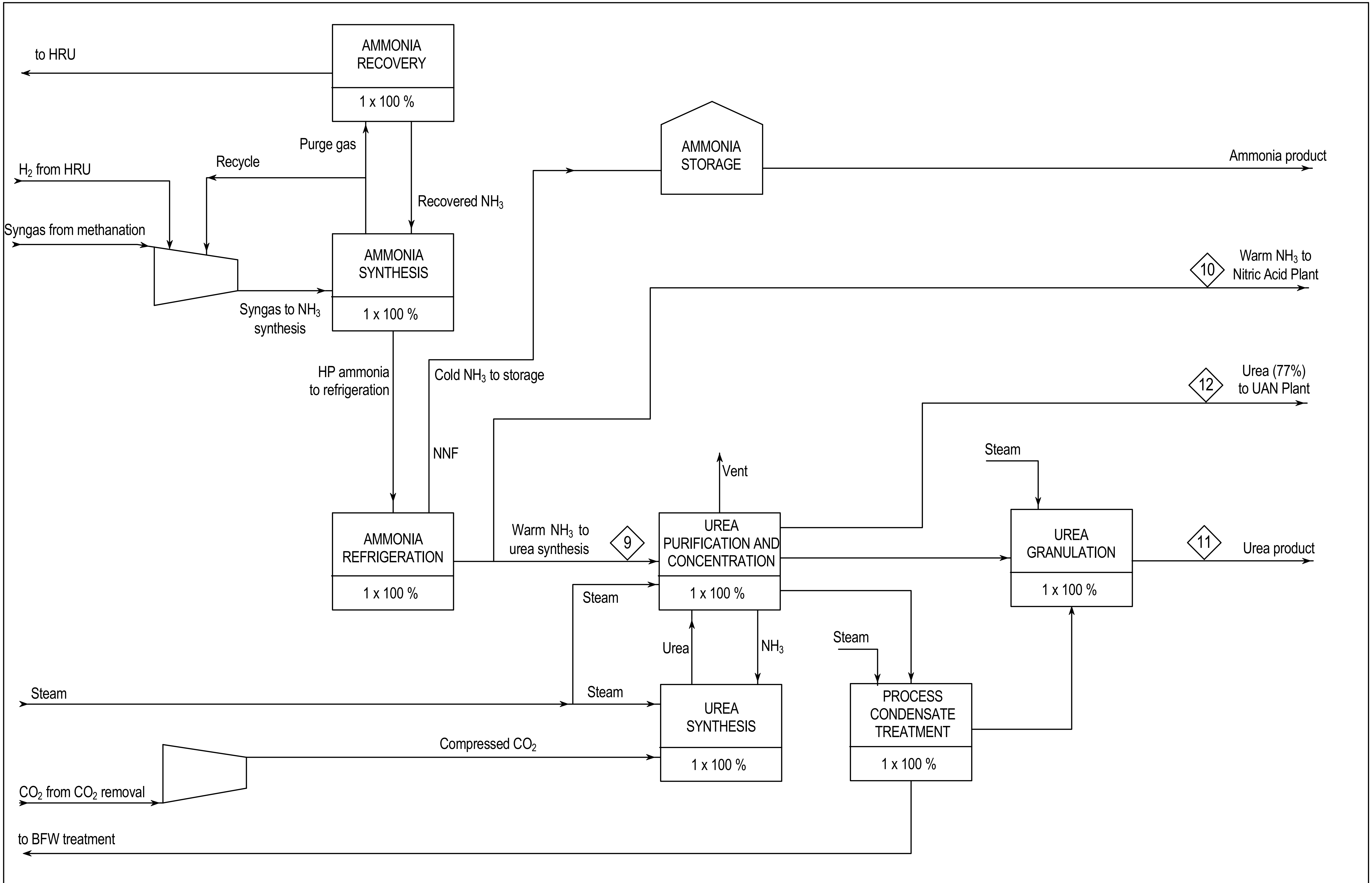
1	11/12/2020		NM	GC	Ammonia and Urea Plant	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas without CO_2 Capture**	**Sheet 02 of 03**



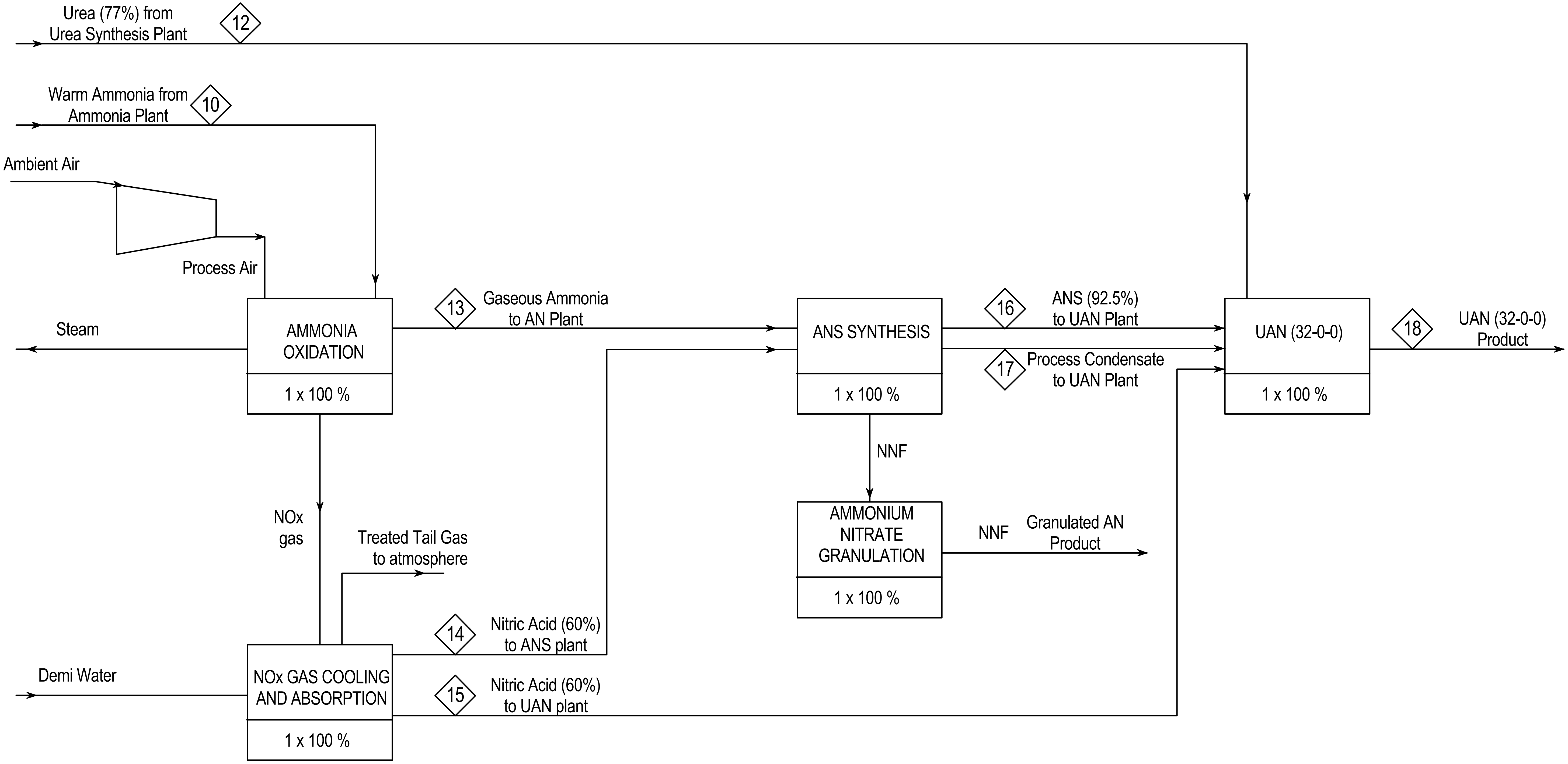
1	11/12/2020		NM	GC	Nitric Acid, Ammonium Nitrate and UAN Plant	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas without CO_2 Capture**	**Sheet 03 of 03**



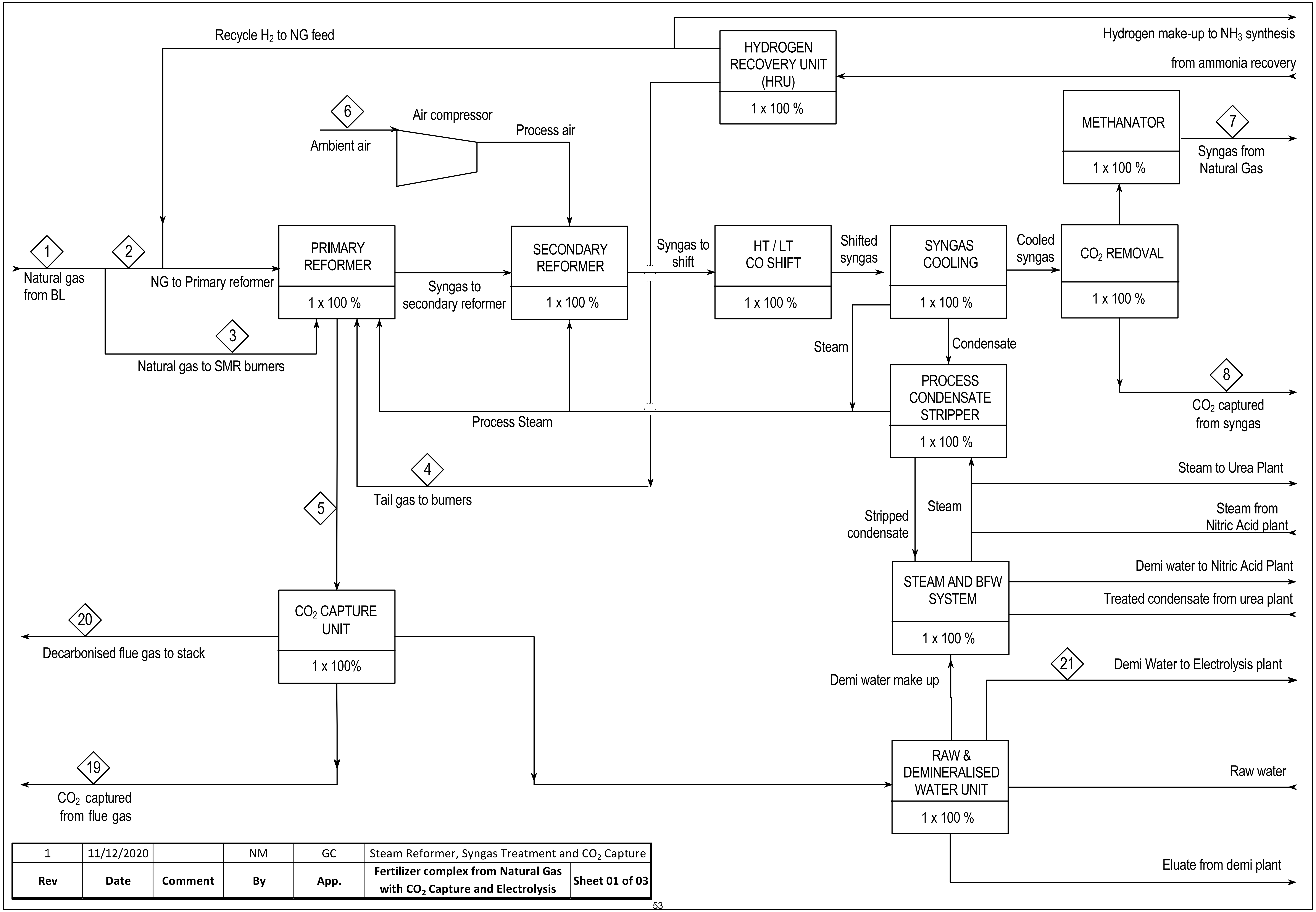
1	11/12/2020		NM	GC	Steam Reformer, Syngas Treatment and CO_2 Capture	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas with CO_2 Capture**	**Sheet 01 of 03**



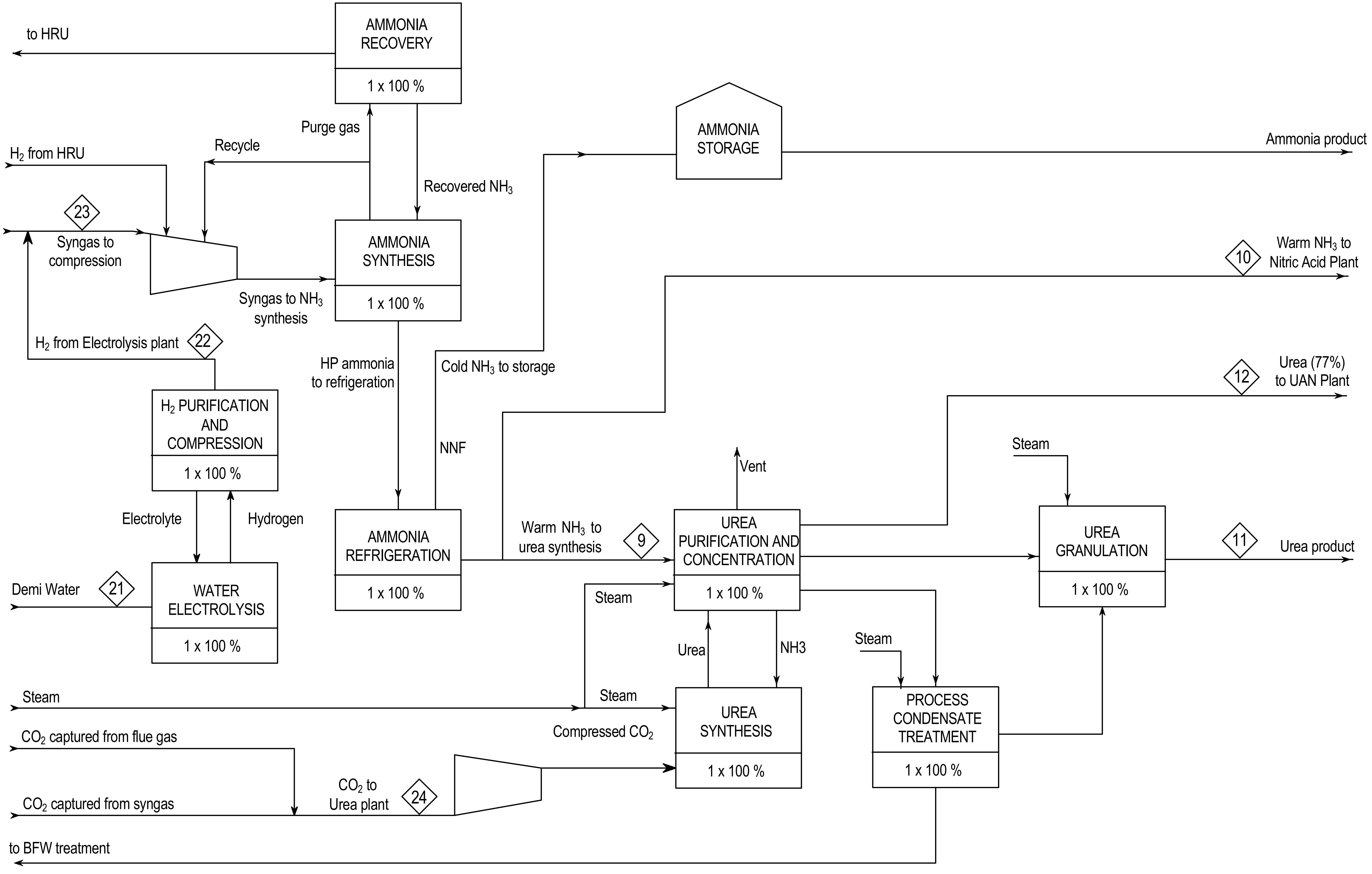
1	11/12/2020		NM	GC	Ammonia and Urea Plant	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas with CO_2 Capture**	**Sheet 02 of 03**



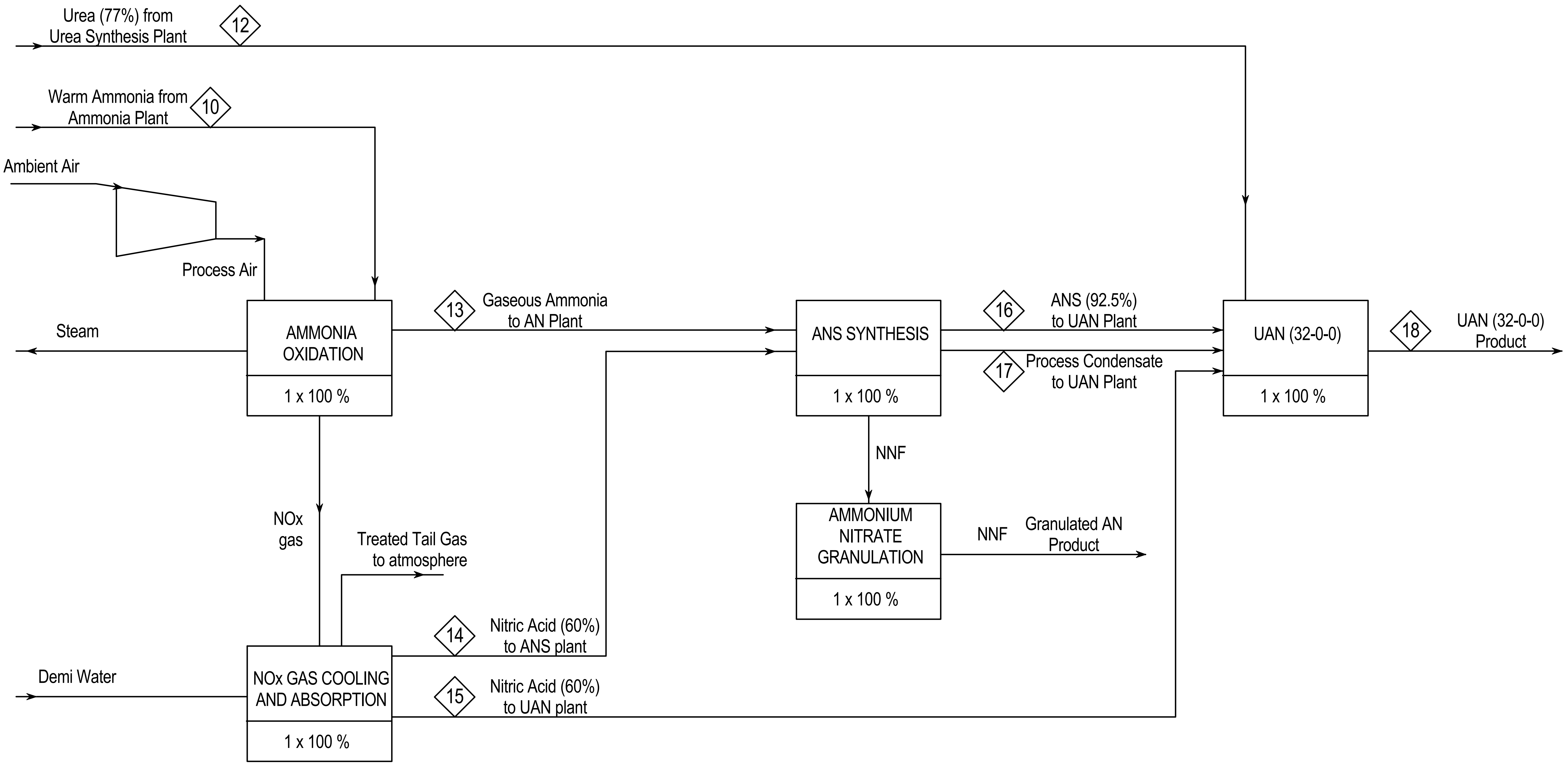
1	11/12/2020		NM	GC	Nitric Acid, Ammonium Nitrate and UAN Plant	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas with CO_2 Capture**	**Sheet 03 of 03**



1	11/12/2020		NM	GC	Steam Reformer, Syngas Treatment and CO_2 Capture	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas with CO_2 Capture and Electrolysis**	**Sheet 01 of 03**



1	11/12/2020		NM	GC	Electrolysis, Ammonia and Urea Plant	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas with CO_2 Capture and Electrolysis**	**Sheet 02 of 03**



1	11/12/2020		NM	GC	Nitric Acid, Ammonium Nitrate and UAN Plant	
Rev	**Date**	**Comment**	**By**	**App.**	**Fertilizer complex from Natural Gas with CO_2 Capture and Electrolysis**	**Sheet 03 of 03**

2.2 TASK 1 – HEAT AND MATERIAL BALANCE

wood.

HEAT AND MATERIAL BALANCE
Natural Gas case without CO2 capture

CLIENT:	IEAGHG	**REV**	**DATE**	**BY**	**CHKD**	**APP**
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION	1	11/12/2020	NM	GC	GC
FWI CONTRACT:	1BD1160A					
LOCATION:	Valid for all locations					

Stream		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Description		Natural Gas From B.L.	Natural Gas feedstock to Ammonia Plant	Natural Gas fuel to burners	Tail gas to burners	Flue gas to stack	Process Air	Syngas to compression	CO_2 to Urea Plant	Ammonia to Urea Plant	Liquid Ammonia to Nitric Acid Plant	Urea product	Urea (77%) to UAN Plant
Temperature	*°C*	9	15	15	50	155	Ambient	43	43	10	10	Ambient	80
Pressure	*Mpa(g)*	7.00	4.20	0.15	0.50	atm	atm	3.00	0.15	2.00	2.00	atm	0.20
Molar Flow	*kmol/h*	3096	2222	874	418	11806	3387	10381	2471	4653	249	2199	251
Mass Flow	*kg/h*	55779	40031	15748	8271	327858	97895	93116	104582	79103	4231	131951	9818
	t/d (100%) product									1898	102	3167	
Composition													
CO_2	*mol/mol*	0.0200	0.0200	0.0200	0.0000	0.0870	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	0.0000
CO	*mol/mol*	0.0000	0.0000	0.0000	0.0000	(2)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydrogen	*mol/mol*	0.0000	0.0000	0.0000	0.2690	0.0000	0.0000	0.7300	0.0080	0.0000	0.0000	0.0000	0.0000
Nitrogen	*mol/mol*	0.0089	0.0089	0.0089	0.4770	0.7070	0.7800	0.2580	0.0010	0.0000	0.0000	0.0000	0.0000
Ar	*mol/mol*	0.0000	0.0000	0.0000	0.0760	0.0120	0.0100	0.0030	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0140	0.2100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	*mol/mol*	0.8900	0.8900	0.8900	0.1780	0.0000	0.0000	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	*mol/mol*	0.0700	0.0700	0.0700	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Propane	*mol/mol*	0.0100	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Butane	*mol/mol*	0.0010	0.0010	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Pentane	*mol/mol*	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.1800	0.0000	0.0020	0.0510	0.0000	0.0000	0.0000	0.4989
NH_3	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000
Urea	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.5011
Nitric Acid	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonium Nitrate	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Contaminants:													
H_2S	*ppm v*	(1)											
NOx	*mg/Nm3*												

Notes:

(1) For feedstock purification section design purposes 5 ppmv of H_2S have been assumed in NG to plant

(2) 30 mg/Nm3 max

wood.

HEAT AND MATERIAL BALANCE
Natural Gas case without CO2 capture

CLIENT:	IEAGHG	**REV**	**DATE**	**BY**	**CHKD**	**APP**
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATI	1	11/12/2020	NM	GC	GC
FWI CONTRACT:	1BD1160A					
LOCATION:	UK					

Stream		**13**	**14**	**15**	**16**	**17**	**18**	**19**
Description		Gaseous Ammonia to Ammonium Nitrate Plant	Nitric Acid (60%) to Ammonium Nitrate Plant	Nitric Acid (60%) to UAN Plant	ANS (92.5%) to UAN Plant	Process condensate to UAN Plant	UAN (32-0-0) Product	
Temperature	*°C*	90	80	80	80	80	10	
Pressure	*Mpa(g)*	0.50	0.50	0.20	0.20	0.20	atm	
Molar Flow	*kmol/h*	121	402	6	164	72	493	
Mass Flow	*kg/h*	2050	12658	182	10406	1297	21703	
	t/d (100%) produc		182	3	231		521	
Composition								
CO_2	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
CO	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Hydrogen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Nitrogen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Ar	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Oxygen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Methane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Ethane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Propane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
n-Butane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
n-Pentane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
H_2O	*mol/mol*	0.0000	0.7000	0.7000	0.2649	1.0000	0.4968	
NH_3	*mol/mol*	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Urea	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.2556	
Nitric Acid	*mol/mol*	0.0000	0.3000	0.3000	0.0000	0.0000	0.0035	
Ammonium Nitrate	*mol/mol*	0.0000	0.0000	0.0000	0.7351	0.0000	0.2441	
Contaminants:								
H_2S	*ppm v*							
NOx	*mg/Nm3*							

Notes:

HEAT AND MATERIAL BALANCE
Natural Gas case with CO2 capture

		REV	DATE	BY	CHKD	APP
CLIENT:	IEAGHG	**REV**	**DATE**	**BY**	**CHKD**	**APP**
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION	1	11/12/2020	NM	GC	GC
FWI CONTRACT:	1BD1160A					
LOCATION:	Valid for all locations					

Stream		1	2	3	4	5	6	7	8	9	10	11	12
Description		Natural Gas From B.L.	Natural Gas feedstock to Ammonia Plant	Natural Gas fuel to burners	Tail gas to burners	Flue gas to stack	Process Air	Syngas to compression	CO_2 to Urea Plant	Ammonia to Urea Plant	Liquid Ammonia to Nitric Acid Plant	Urea product	Urea (77%) to UAN Plant
Temperature	*°C*	9	15	15	50	155	Ambient	43	43	10	10	Ambient	80
Pressure	*Mpa(g)*	7.00	4.20	0.15	0.50	atm	atm	3.00	0.15	2.00	2.00	atm	0.20
Molar Flow	*kmol/h*	3096	2222	874	418	11806	3387	10381	2471	4653	249	2199	251
Mass Flow	*kg/h*	55779	40031	15748	8271	327858	97895	93116	104582	79103	4231	131951	9818
	t/d (100%) product									1898	102	3167	
Composition													
CO_2	*mol/mol*	0.0200	0.0200	0.0200	0.0000	0.0870	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	0.0000
CO	*mol/mol*	0.0000	0.0000	0.0000	0.0000	(2)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydrogen	*mol/mol*	0.0000	0.0000	0.0000	0.2690	0.0000	0.0000	0.7300	0.0080	0.0000	0.0000	0.0000	0.0000
Nitrogen	*mol/mol*	0.0089	0.0089	0.0089	0.4770	0.7070	0.7800	0.2580	0.0010	0.0000	0.0000	0.0000	0.0000
Ar	*mol/mol*	0.0000	0.0000	0.0000	0.0760	0.0120	0.0100	0.0030	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0140	0.2100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	*mol/mol*	0.8900	0.8900	0.8900	0.1780	0.0000	0.0000	0.0070	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	*mol/mol*	0.0700	0.0700	0.0700	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Propane	*mol/mol*	0.0100	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Butane	*mol/mol*	0.0010	0.0010	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Pentane	*mol/mol*	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.1800	0.0000	0.0020	0.0510	0.0000	0.0000	0.0000	0.4989
NH_3	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000
Urea	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.5011
Nitric Acid	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonium Nitrate	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Contaminants:													
H_2S	*ppm v*	(1)											
NOx	*mg/Nm3*												

Notes:

(1) For feedstock purification section design purposes 5 ppmv of H_2S have been assumed in NG to plant

(2) 30 mg/Nm3 max

wood.

HEAT AND MATERIAL BALANCE
Natural Gas case with CO2 capture

CLIENT:	IEAGHG	**REV**	**DATE**	**BY**	**CHKD**	**APP**
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PR	1	11/12/2020	NM	GC	GC
FWI CONTRACT:	1BD1160A					
LOCATION:	Valid for all locations					

Stream		**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Description		Gaseous Ammonia to Ammonium Nitrate Plant	Nitric Acid (60%) to Ammonium Nitrate Plant	Nitric Acid (60%) to UAN Plant	ANS (92.5%) to UAN Plant	Process condensate to UAN Plant	UAN (32-0-0) Product	CO_2 Product	Decarbonized Flue gas to stack	
Temperature	°C	90	80	80	80	80	10	24	43	
Pressure	Mpa(g)	0.50	0.50	0.20	0.20	0.20	atm	11.00	0.10	
Molar Flow	kmol/h	121	402	6	164	72	493	924	8921	
Mass Flow	kg/h	2050	12658	182	10406	1297	21703	40674	252148	
	t/d (100%) produc		182	3	231		521	976		
Composition										
CO_2	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9999+	0.0115	
CO	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	(2)	
Hydrogen	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Nitrogen	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9356	
Ar	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0159	
Oxygen	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0185	
Methane	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Ethane	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Propane	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
n-Butane	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
n-Pentane	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
H_2O	mol/mol	0.0000	0.7000	0.7000	0.2649	1.0000	0.4968	0.0000	0.0185	
NH_3	mol/mol	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
Urea	mol/mol	0.0000	0.0000	0.0000	0.0000	0.0000	0.2556	0.0000	0.0000	
Nitric Acid	mol/mol	0.0000	0.3000	0.3000	0.0000	0.0000	0.0035	0.0000	0.0000	
Ammonium Nitrate	mol/mol	0.0000	0.0000	0.0000	0.7351	0.0000	0.2441	0.0000	0.0000	
Contaminants:										
H_2S	ppm v									
NOx	mg/Nm3									

Notes:

wood.

HEAT AND MATERIAL BALANCE
Hybrid Natural Gas/Electrolysis case with CO2 capture

CLIENT:	IEAGHG	**REV**	**DATE**	**BY**	**CHKD**	**APP**
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION	1	11/12/2020	NM	GC	GC
FWI CONTRACT:	1BD1160A					
LOCATION:	Valid for all locations					

Stream		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Description		Natural Gas from B.L.	Natural Gas feedstock to Ammonia Plant	Natural Gas fuel to burners	Tail gas to burners	Flue gas to capture unit	Process Air	Syngas from Natural Gas	CO_2 captured from Syngas	Ammonia to Urea Plant	Liquid Ammonia to Nitric Acid Plant	Urea product	Urea (77%) to UAN Plant	Gaseous Ammonia to Ammonium Nitrate Plant
Temperature	*°C*	9	15	15	50	155	Ambient	43	43	10	10	Ambient	80	90
Pressure	*Mpa(g)*	7.00	4.20	0.15	0.50	atm	atm	3.00	0.15	2.00	2.00	atm	0.20	0.50
Molar Flow	*kmol/h*	2199	1682	516	292	7125	3428	8152	1810	4653	249	2199	251	121
Mass Flow	*kg/h*	39615	30315	9300	5778	198467	99058	88555	78659	79103	4231	131951	9818	2050
	t/d (100%) product									1898	102	3167		
Composition														
CO_2	*mol/mol*	0.0200	0.0200	0.0200	0.0000	0.0859	0.0000	0.0000	0.9791	0.0000	0.0000	0.0000	0.0000	0.0000
CO	*mol/mol*	0.0000	0.0000	0.0000	0.0000	(2)	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Hydrogen	*mol/mol*	0.0000	0.0000	0.0000	0.2690	0.0000	0.0000	0.6575	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nitrogen	*mol/mol*	0.0089	0.0089	0.0089	0.4770	0.7141	0.7800	0.3292	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	*mol/mol*	0.0000	0.0000	0.0000	0.0760	0.0117	0.0100	0.0041	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0152	0.2100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Methane	*mol/mol*	0.8900	0.8900	0.8900	0.1780	0.0000	0.0000	0.0064	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	*mol/mol*	0.0700	0.0700	0.0700	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Propane	*mol/mol*	0.0100	0.0100	0.0100	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Butane	*mol/mol*	0.0010	0.0010	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
n-Pentane	*mol/mol*	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H_2O	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.1731	0.0000	0.0028	0.0209	0.0000	0.0000	0.0000	0.4989	0.0000
NH_3	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0000	1.0000	1.0000	0.0000	0.0000	1.0000
Urea	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.5011	0.0000
Nitric Acid	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ammonium Nitrate	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Contaminants:														
H_2S	*ppm v*	(1)												
NOx	*mg/Nm3*													

Notes:

(1) For feedstock purification section design purposes 5 ppmv of H_2S have been assumed in NG to plant

(2) 30 mg/Nm3 max

HEAT AND MATERIAL BALANCE
Hybrid Natural Gas/Electrolysis case with CO2 capture

CLIENT:	IEAGHG	**REV**	**DATE**	**BY**	**CHKD**	**APP**
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION	1	11/12/2020	NM	GC	GC
FWI CONTRACT:	1BD1160A					
LOCATION:	Valid for all locations					

Stream		**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Description		Nitric Acid (60%) to Ammonium Nitrate Plant	Nitric Acid (60%) to UAN Plant	ANS (92.5%) to UAN Plant	Process condensate to UAN Plant	UAN (32-0-0) Product	CO_2 captured from Flue Gas	Decarbonized Flue gas to stack	Demi Water to Electrolysis Plant	H_2 from Electrolysis Plant	Syngas to compression	CO_2 to Urea Plant		
Temperature	*°C*	80	80	80	80	10	43	43	Ambient	43	43	43		
Pressure	*Mpa(g)*	0.50	0.20	0.20	0.20	atm	0.15	0.10	atm	3.00	3.00	0.15		
Molar Flow	*kmol/h*	402	6	164	72	493	562	5866	2363	2233	10384	2372		
Mass Flow	*kg/h*	12658	182	10406	1297	21703	24535	161415	42535	4465	93021	103194		
	t/d (100%) produc	182	3	231		521				107				
Composition														
CO_2	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.9791	0.0104	0.0000	0.0000	0.0000	0.9791		
CO	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	(2)	0.0000	0.0000	0.0000	0.0000		
Hydrogen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.9999+	0.7311	0.0000		
Nitrogen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.8672	0.0000	0.0000	0.2584	0.0000		
Ar	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0143	0.0000	0.0000	0.0032	0.0000		
Oxygen	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0185	0.0000	0.0000	0.0000	0.0000		
Methane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0050	0.0000		
Ethane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Propane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
n-Butane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
n-Pentane	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
H_2O	*mol/mol*	0.7000	0.7000	0.2649	1.0000	0.4968	0.0209	0.0896	1.0000	0.0000	0.0022	0.0209		
NH_3	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Urea	*mol/mol*	0.0000	0.0000	0.0000	0.0000	0.2556	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Nitric Acid	*mol/mol*	0.3000	0.3000	0.0000	0.0000	0.0035	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Ammonium Nitrate	*mol/mol*	0.0000	0.0000	0.7351	0.0000	0.2441	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
Contaminants:														
H_2S	*ppm v*													
NOx	*mg/Nm3*													

Notes:

2.3 TASK 1 – PROCESS DESCRIPTION

Client	:	IEAGHG
Project Name	:	Feasibility Study on Achieving Deep Decarbonization in Worldwide Fertilizer Production
Document Name	:	Process Description
AmecFWI contract	:	1-BD-1160A

ISSUED BY	:	N. Marzorati
CHECKED BY	:	G. Collodi
APPROVED BY	:	G. Collodi

Date	Revised Pages	Issued by	Checked by	Approved by
03/2021				

TABLE OF CONTENTS

1. Case 1: Ammonia production from Natural Gas without Carbon Capture

1.1. Process Description

There are various technologies used in the production of ammonia, urea, nitric acid, and ammonium nitrate that are commercially available. The process scheme selected for this study is generic, with no reference to specific licensor and equipment suppliers.

The process scheme is the same for all the four locations analysed. The only exception is represented by the presence of a seawater desalination plant for the Middle East case.

1.1.1. Ammonia Plant

Ammonia is produced by conversion of the hydrogen (H_2) and nitrogen (N_2) contained in “synthesis gas” or “syngas” with a typical molar ratio of approximately 3:1.

Hydrogen is supplied by reforming of hydrocarbon feedstock; whilst the nitrogen is supplied by introducing the process air into the secondary reformer. For this case, natural gas is the main hydrocarbon feedstock.

The steps to produce ammonia are as follows:

- The hydrocarbon feed is pre-treated by removing any sulphur and chloride. A pre-reformer can be employed to ease the load of the primary reformer.
- The treated hydrocarbon feed is reformed in a two-steps reformer (which consists of the Steam Methane Reformer unit as the primary reformer and the air blown Auto Thermal Reformer as the secondary reformer) to produce the raw syngas which mainly consists of H_2, N_2, CO, CO_2, CH_4, Ar and steam.
- The raw syngas is further purified to remove any CO and CO_2 (as the ammonia synthesis catalyst is poisoned by oxygenated compounds). This involves (a.) the conversion of CO in the high and low temperature shift reactors; (b.) the bulk removal of CO_2 using chemical absorption; and (c.) the polishing step to remove any remaining CO and CO_2 in the methanation reactor
- The purified syngas is compressed and then sent to the ammonia synthesis loop where it is converted to liquid ammonia.

A generic simplified block flow diagram of the overall ammonia plant is shown in the following pages.

Desulphurization Section

The natural gas feedstock, which could contain up to 5 ppm (v/v) of sulphur compounds, must be desulphurised, as the primary reformer catalyst and the low temperature CO shift catalysts are poisoned by sulphur compounds.

The desulphurisation takes place in two stages – (1.) the hydrogenation of any organic sulphur and the saturation of any olefins; and (2.) removal of H_2S.

ZnO absorber is used to remove any H_2S in the feedstock and should bring this down to less than 0.05 ppm (v/v) H_2S.

Pre-Reformer

The Pre-Reformer is an adiabatic reactor that, if present, is mainly responsible for converting any heavy hydrocarbons in the feed to CH_4 and other co-products (i.e. CO_2, CO and H_2).

Primarily, it takes over part of the overall reforming duty of the SMR – i.e. by transferring some of the reformer duty from SMR to the Pre-Reformer, the efficiency of the process is increased. The residual C_2+ in the product gas of the Pre-Reformer is regulated not to exceed 500 ppmv (max).

Reforming Section

The desulphurised feedstock is reformed in the primary and secondary reformer to produce the H_2 needed for the ammonia synthesis.

In the Primary Reformer the hydrocarbon feedstock reacts with steam in the bank of reformer tubes packed with nickel catalyst, at 800 to 900°C and at 3 to 25 Bar(g). The syngas produced mainly consists of H_2, CO_2, CO, CH_4 and steam.

The main reaction regulating the process is the Steam Methane Reforming reaction:

$$CH_4 + H_2O + \text{Heat} \quad \Leftrightarrow \quad CO + 3H_2$$

In order to avoid carbon formation on the catalyst by cracking reactions, excess steam is introduced in the feedstock. This leads to the formation of carbon dioxide and additional hydrogen through the Water Gas Shift reaction:

$$CO + H_2O \Leftrightarrow CO_2 + H_2 + heat$$

The heat required by the reaction is supplied indirectly by burning the tail gas and supplementary fuel in the SMR furnace.

As compared to the conventional SMR (normally used in H_2 production), the operation of the primary reformer is less intensive, which allows a higher methane slip (up to 10%v)

The Secondary Reformer is based on the principle of air blown auto-thermal reforming (ATR).

The introduction of air in the secondary reformer provides the nitrogen required for the synthesis of ammonia.

In the ATR, the main heat is supplied by the combustion (in sub-stoichiometric condition) of the gas mixture obtained from the primary reformer and air. The combustion occurs in the upper section (combustion chamber or mixing volume) of the ATR. The lower section of the ATR consists of the catalyst bed which reforms the partially combusted gas mixture to produce the desired amount of hydrogen needed for the ammonia synthesis. Additionally, due to the higher operating temperature, methane slip is reduced to less than 0.8%v.

Since the molar ratio (H_2/N_2) are fixed to maintain a value as close to 3, the amount of process air introduced into the ATR is fixed. To control the methane slip from the ATR, the firing of the primary reformer (i.e. temperature of the SMR) is adjusted accordingly.

The gas leaving the ATR is around 1000°C. Cooling of the syngas is carried out in the Waste Heat Boiler, to produce high pressure (HP) steam.

Shift Section

The syngas leaving the reforming section contains substantial amount of CO. This is converted to CO_2 and H_2 via Water Gas Shift reaction.

The shift reaction takes place in two different adiabatic reactors in series. The first reactor is the high temperature shift (HTS) reactor using iron-based catalyst promoted by chromium oxides or copper oxides. This operates at around 350-360°C. Residual CO of around 2-3% (dry basis) is expected.

The gas leaving from the first reactor is then cooled to around 180-200°C before being introduced into the low temperature shift reactor (LTS) using copper catalyst. Residual CO of around 0.1-0.3% (dry basis) should be expected. The gas leaving the low temperature shift reactor is then cooled to around 50°C before being delivered to the bulk CO_2 removal section.

Overall, ~95% of the CO that is fed into the two shift reactors should be converted into CO_2.

Bulk CO_2 Removal Section

The bulk of the CO_2 in the syngas is removed by using a generic absorption process (based on aMDEA solvent)[1].

The process mainly consists of the absorber, flash column, rich-lean HX, and regenerator columns. The CO_2 is removed from the syngas by contacting with the solvent at high pressure. The rich solvent is then delivered to the flash column at lower pressure so that the volatiles are released into the gas phase. This gaseous stream is sent to the burners of the SMR. The remaining CO_2 rich solution is then pre-heated by the lean solution before being fed into the upper section of the regeneration column, where CO_2 is released into the vapour phase by steam stripping.

The CO_2 released from the solvent in the regeneration column is then sent to the Urea Plant as feedstock to the urea production.

Calculation have been developed according to Wood internal database. A simplified approach has been followed: no amine emission or make up have been considered.

Methanation Section

Any oxygen containing compounds, such as CO and CO_2, are severe poison to the ammonia synthesis catalyst.

To remove any residual CO and CO_2 from the syngas, the methanation process is used as a polishing step. This process takes place in the Methanator and involves the following reactions:

$$CO + 3H_2 \Leftrightarrow CH_4 + H_2O + heat$$
$$CO_2 + 4H_2 \Leftrightarrow CH_4 + 2H_2O + heat$$

Besides the activity of the catalyst, the temperature, pressure, and moisture content of the syngas determine the conversion efficiency of the methanation reactions. Lower temperature, higher pressure and lower water vapour content favour the methane formation.

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[1] It should be noted that there are several other technologies that could be used in the bulk removal of CO_2 from the shifted syngas. Some of the notable examples include chemical absorption – i.e. aMDEA (BASF), Hot Potassium Carbonate (Giammarco-Vetrocoke and UOP); physical absorption – i.e. Rectisol (Linde, Lurgi), Selexol (UOP), etc…

The methanation reactions are exothermic. In normal operation, temperature rise of around 20°C is generally expected.

After the methanation step, the purified syngas that is fed into the ammonia synthesis loop is mostly N_2 and H_2 with approximately 1% (mol) of Ar and CH_4 and less than 5 ppm (mol) of CO and CO_2.

Ammonia Synthesis Section

The ammonia synthesis takes place in the Ammonia Synthesis Converter according to the following reaction:

$$3H_2 + N_2 \quad \Leftrightarrow \quad 2NH_3 + \text{heat}$$

The reaction is reversible. In the ammonia synthesis converter, about 25 - 30% of the N_2 and the H_2 are converted into NH_3. The unconverted part is recycled to the converter after separation of the liquid ammonia product.

Higher pressure and lower temperature favour the formation of ammonia. As the reaction is exothermic, the choice of the operating temperature is based on a compromise between the theoretical conversion and approach to equilibrium.

The normal operating pressure of modern ammonia synthesis may vary between 130 and 220 Bar(g) (inlet of the ammonia converter), depending on load and catalyst activity. The normal operating temperatures are in the range of approx. 370-500°C.

The heat liberated by the reaction (about 750 kcal/kg produced ammonia) is typically utilised to generate high/medium pressure steam and to pre-heat the boiler feed water and the converter feed gas.

After the synthesis gas passes through the converter, the effluent gas is cooled to about 0°C in the ammonia chillers where most of the ammonia is condensed. The condensed ammonia is then separated from the effluent gas in the ammonia separator.

The recycling of the effluent gas from the converter is generally carried out in the recirculator which is an integral part of the syngas compressor (where the syngas from the methanator is compressed to the synthesis loop pressure).

From the separator, the effluent gas is recycled back to the ammonia synthesis converter through the cold heat exchanger, the recirculating stage of the compressor, and then finally through the hot heat exchanger.

Purge Gas System – Inert Gases Removal

The purified synthesis gas from the methanator contains a small amount of inert gases, mainly Ar and CH_4. These inerts could accumulate due to the recycling of the effluent gas to the ammonia synthesis converter.

A high level of inert gases tends to inhibit the formation of ammonia (thus requiring large catalyst volume or very high operating pressure). To avoid the accumulation of the inert gases, a continuous purge from the synthesis loop is required.

A large portion of the inerts are removed through the purge gas system. The purge gas is then sent to the ammonia and hydrogen recovery unit to recover any ammonia (which is mainly recycled back to the ammonia synthesis loop) and hydrogen (which is used as feedstock to the hydrogenation unit), whilst the tail gas is then sent to the SMR as fuel.

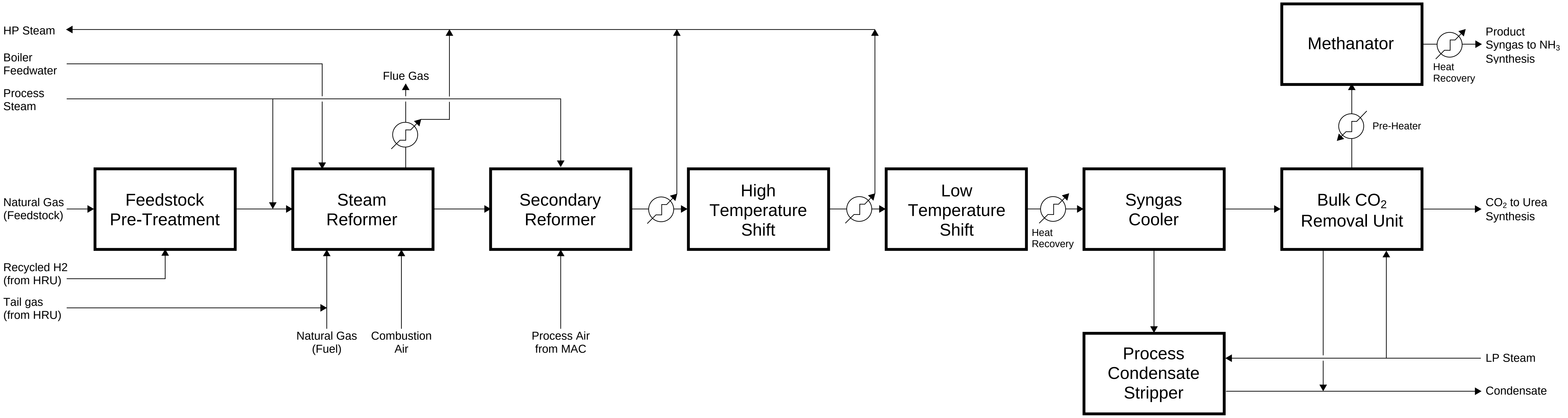
A small part of the inerts could also be dissolved in the liquid product; and these are normally released during the let-down of the liquid product in the NH_3 separator. The quantity of inert gas leaving the loop this way is proportional to the partial pressure of the inerts (inert level).

Refrigeration

The purpose of the refrigeration circuit is to carry out the various cooling duties within the ammonia synthesis loop. The primary task is to condense the ammonia, which is produced in the converter. Other cooling duties include the cooling of the purge gas, let-down gas, and inert gas.

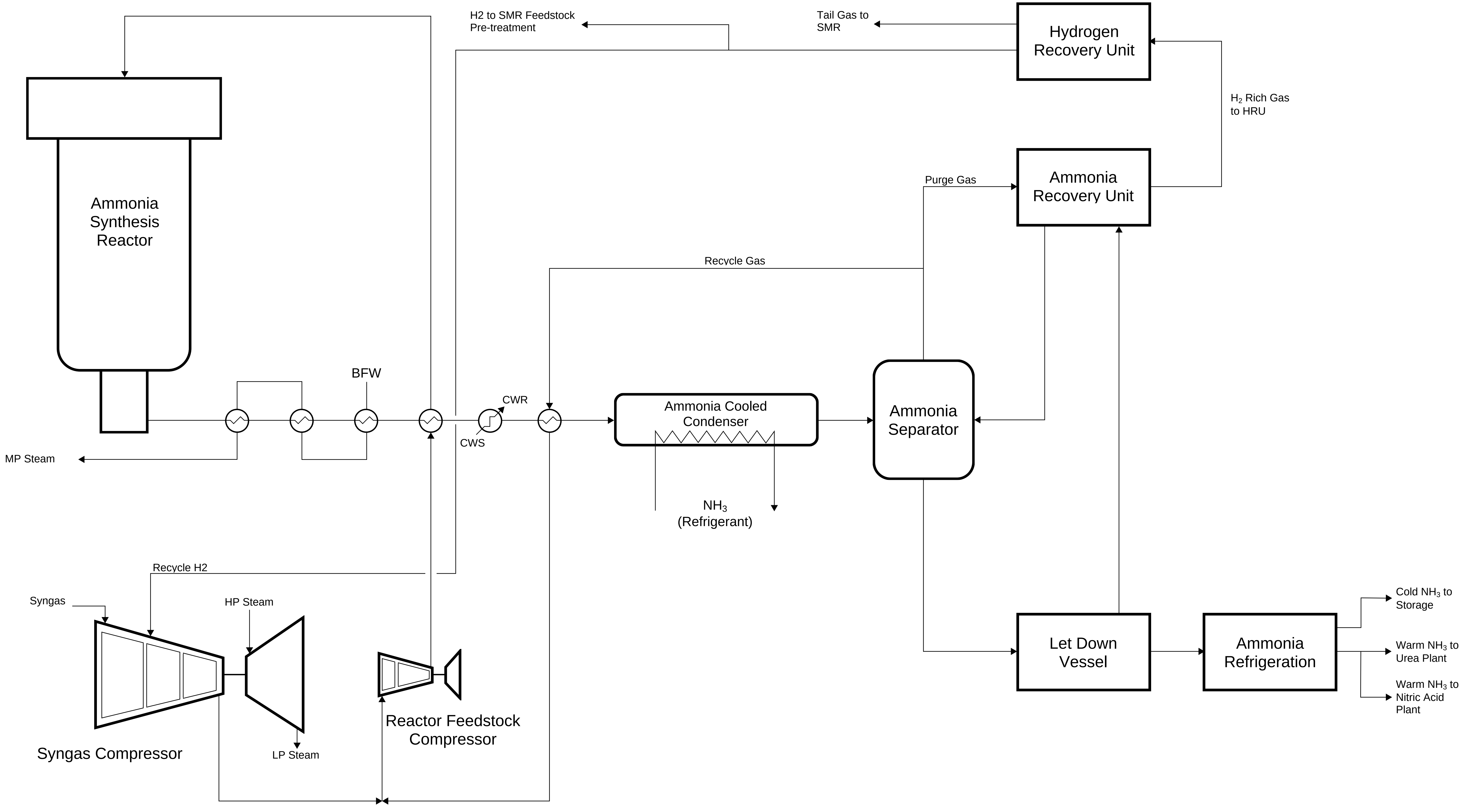
The refrigeration circuit typically includes the following main equipment: four chillers operating at two different pressure levels, the refrigeration compressor, the ammonia booster compressor, the ammonia condenser and finally the ammonia accumulator.

Liquid ammonia can be produced at different pressure/temperature levels depending on its final use. If ammonia is converted into urea, nitric acid or ammonium nitrate, then ammonia is sent to the Urea Plant at 10-15°C and 10-20 Bar(g); otherwise ammonia is stored in cryogenic atmospheric storage tanks at -33°C.



SCHEMATIC BLOCK FLOW DIAGRAM

SYNGAS GENERATION & TREATMENT SECTION (NO CCS)



SCHEMATIC BLOCK FLOW DIAGRAM

AMMONIA SYNTHESIS PLANT

1.1.2. Urea Plant

Urea is produced from the synthesis of liquid NH_3 and gaseous CO_2, both produced in the Ammonia Plant.

In the urea reactor the ammonia and carbon dioxide react to form ammonium carbamate, a portion of which is dehydrated to form the urea and water. The reactions are as follows:

$$2NH_3 + CO_2 \quad \leftrightarrow \quad NH_2\text{-}COO\text{-}NH_4$$
$$+\ 32560\ \text{kcal/kmol of carbamate (at 1 atm; 25°C);}$$

$$NH_2\text{-}COO\text{-}NH_4 \quad \leftrightarrow \quad NH_2\text{-}CO\text{-}NH_2 + H_2O$$
$$-\ 4200\ \text{kcal/kmol of urea (at 1 atm; 25°C)}$$

The first reaction occurs rapidly to completion; whilst the second reaction occurs slowly, and this determines the reactor volume.

The Urea Plant primarily consists of the (a.) synthesis reactor, (b.) stripper, (c.) carbamate condenser, (d.) decomposers, (e.) vacuum concentrator, (f.) evaporator; and (g.) granulation plant.

Figures shown in the succeeding pages present the generic block flow diagram of the urea synthesis and Urea Granulation Plant.

Depending on the licensor, the urea synthesis reactor is typically operated at around 190°C and 150-160 Bar(g).

The fraction of ammonium carbamate that dehydrates is determined by the ratios of the various reagents, operating temperature, pressure and their residence time in the reactor.

The CO_2 (with a purity of at least 98.5% vol. and at 0.5 to 0.75 Bar(g)), coming mainly from the Bulk CO_2 Removal Section, is compressed to about 160 Bar(g).

Downstream the urea synthesis the decomposition (and relevant recovery) of unconverted chemical reagents is carried out in several subsequent steps at lower pressures. The decomposition reaction is the reverse reaction of the first one above showed:

$$NH_2\text{-}COO\text{-}NH_4 \quad \leftrightarrow \quad 2NH_3 + CO_2\ \text{(- Heat)}$$

and, as can be inferred from the equation, it is promoted by reducing pressure and/or adding heat.

In order to granulate urea, the urea solution has to be concentrated up to 96% wt. At this purpose, one vacuum concentration stage is necessary.
Hence, the solution leaving the decomposer bottom at low pressure with about 70 % wt. urea is first sent to the vacuum pre-concentrator. Then, the urea solution leaving the bottom of vacuum pre-concentrator is pumped to the vacuum concentrator. Low pressure saturated steam is supplied to concentrate the urea solution.

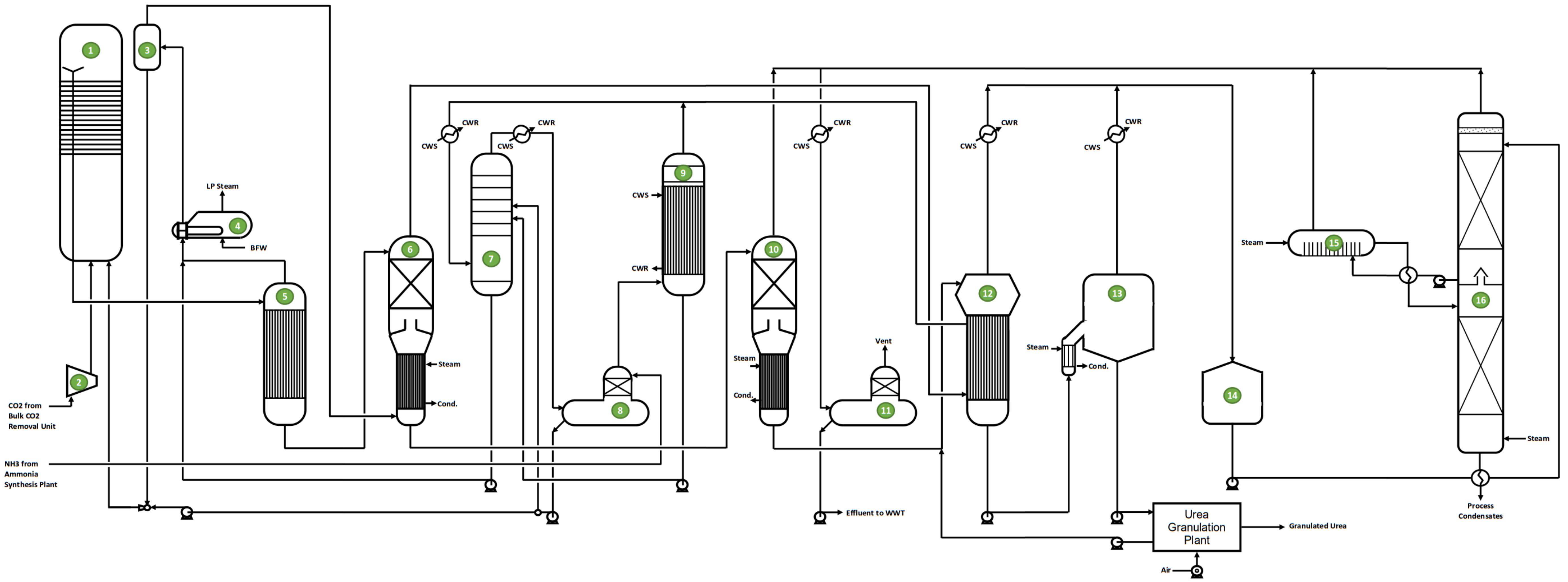
The mixed phase coming out from the concentrator enters the gas-liquid vacuum separator, from which vapours are extracted by the vacuum system, while the urea solution (~ 96 % by wt.), is sent to the granulation unit.

The process water containing NH_3, CO_2 and urea, coming from the vacuum system, is collected and sent to a urea hydrolyser, where process conditions are suitable to decompose urea into CO_2 and NH_3 so as to have an almost NH_3-CO_2, urea free, process condensate to be recovered as boiler feed water.

The concentrated urea solution (~ 96 % by wt.) is fed to the injection heads of the granulation unit where it is finely atomized, assisted by air. Fluidization air flows through the product layer to create a fluid bed and is discharged at the granulator top. Granulated urea flows from the granulator to a cooler and then to the screening section. The fine fraction is recycled directly to the granulator while the coarse material is crushed before being sent to the granulator. The final urea product is then sent to warehouse after final cooling.

For the case without carbon capture from flue gases of the SMR, all the CO_2 available from the ammonia plant is employed to produce urea, and the corresponding quantity of ammonia is fed to the Urea Plant. All the remaining ammonia is sent to the Nitric Acid and Ammonium Nitrate Plant, which is entirely utilized to produce UAN.

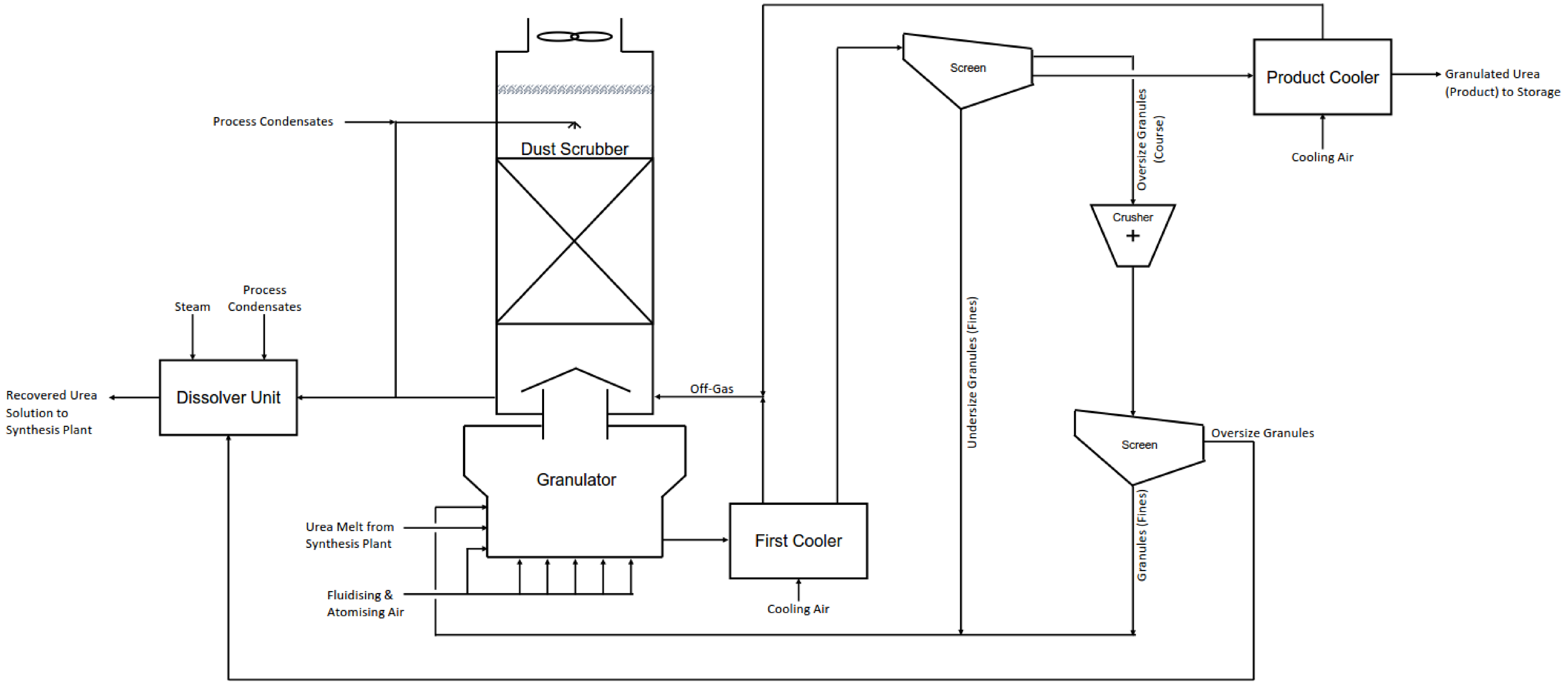
A stream of urea is pumped from the Urea Synthesis Plant to the UAN plant in a 77% solution with water.



1	Urea synthesis reactor	9	Flash tank condenser
2	CO2 compressor	10	LP decomposer
3	Separator	11	Blowdown tank
4	Carbamate condenser	12	Concentrator / pre-evaporator
5	Stripper	13	Vacuum evaporator
6	MP decomposer	14	Ammonia water storage tank
7	Carbamate absorber condenser	15	Hydrolyser
8	Ammonia receiver condenser	16	Process condensate stripper

SCHEMATIC BLOCK FLOW DIAGRAM

UREA SYNTHESIS PLANT



SCHEMATIC BLOCK FLOW DIAGRAM

UREA GRANULATION PLANT

1.1.3. Nitric Acid plant

Nitric acid is obtained from the oxidation of vaporized NH_3 with air, and absorption in water of the resulting products.

The first reaction takes place in the Ammonia Oxidizer, where ammonia is mixed with air over a platinum/rhodium catalyst gauze at approximately 900°C forming nitric oxide and water.

$$4NH_3 + 5O_2 \quad \rightarrow \quad 4NO + 6H_2O + heat$$

Subsequently, nitric oxide reacts slowly with excess oxygen, at low temperatures (preferably below 150°C), producing nitric dioxide. The formation of dinitrogen tetroxide occurs at low temperature and high pressure, in equilibrium with its dimer nitric dioxide. The reaction starts occurring in the equipment between the oxidizer and the absorption tower and is completed within the absorption tower.

$$2NO + O_2 \quad \rightarrow \quad 2NO_2 \quad \leftrightarrow \quad N_2O_4$$

Finally, nitrogen dioxide and its dimer are at the same time absorbed in water at low temperature in the absorption tower, forming nitric acid and some nitric oxide (the latter re-oxidized and reabsorbed).

$$3NO_2 + H_2O \quad \rightarrow \quad 2HNO_3 + NO$$

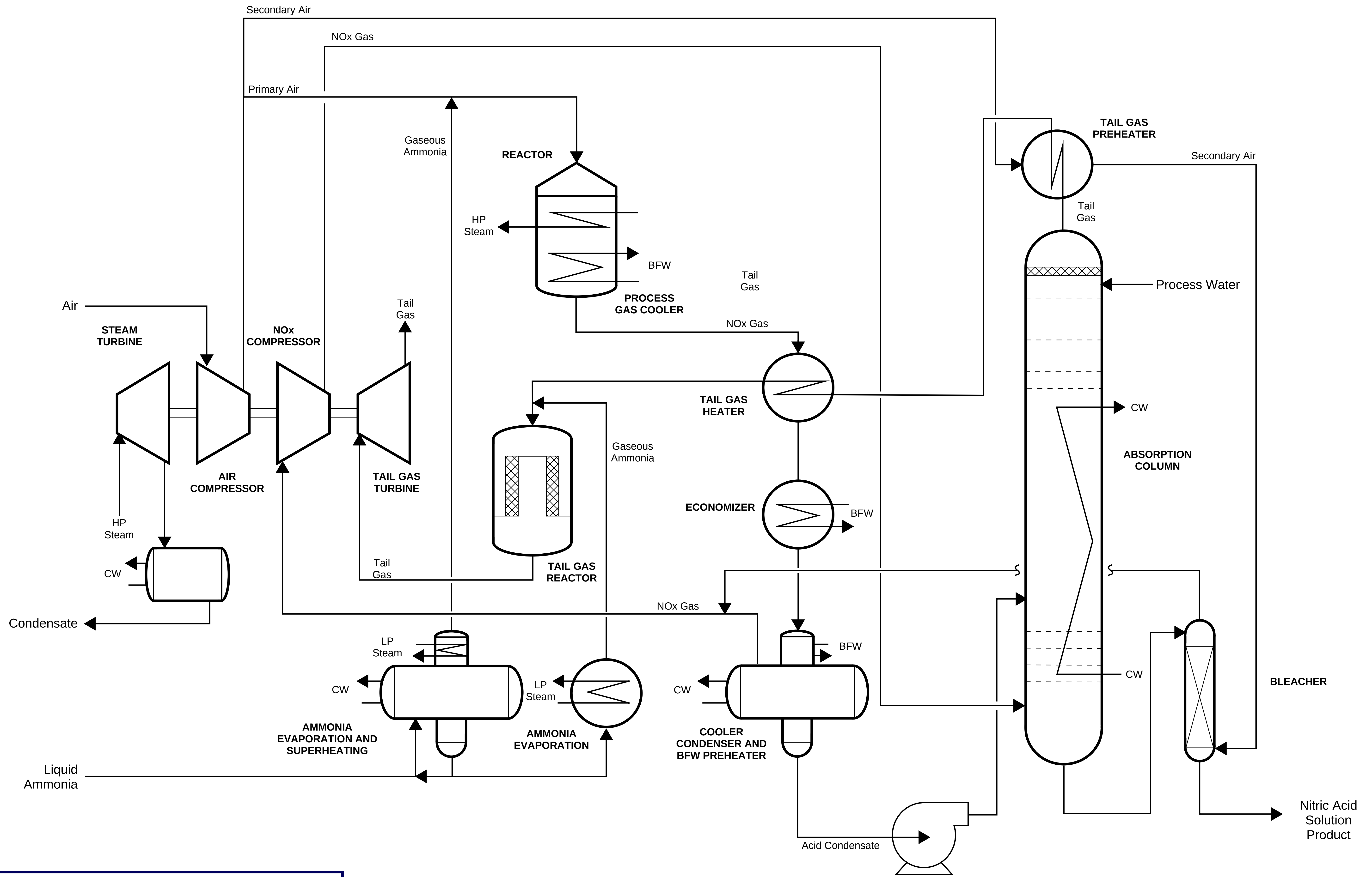
In order to produce a weak acid solution (60% solution in this case), two main technologies are commercially available: the mono pressure and the dual pressure process. The main difference between the two is the number of pressure levels kept inside the plant: for the mono pressure process, the whole plant operates at the same pressure level, which can be medium (2-5 Bar(g)) or high (6-11 Bar(g)); conversely, in the dual pressure the reactor is operated at medium pressure (2-5- Bar(g)), while the absorption column is kept at high pressure (10-14 Bar(g)).

It is assumed that a dual pressure process will be employed, as it better allows to contain NO_x emissions from the tail gas and ensures lower catalyst losses.

A typical generic Dual Pressure process scheme is illustrated in the following pages.

Ammonia is introduced in the reactor after being filtered, vaporized and superheated. Air is supplied in excess by means of a compressor driven by a combination of an HP condensing steam turbine and a tail gas turbine. A small portion of the compressed air is sent to the bleacher.

Hot effluent gases from the reactor are cooled in a series of heat exchangers which includes: a waste heat boiler, in which HP steam is generated, a tail gas heater, an economizer, a boiler feed water pre-heater, and a condenser, in which process gases are finally condensed in a 40-50% wt. solution which is pumped into the absorption tower.



SCHEMATIC BLOCK FLOW DIAGRAM

NITRIC ACID PLANT
DUAL PRESSURE PROCESS

HP steam produced is expanded in the steam turbine inside the plant. Excess steam can be exported to other steam users, like the Urea Plant.

The cooled process gas from the condenser is compressed and injected at the bottom of the absorption tower. The compressor is generally driven by the combination of steam and tail gas turbines.

In order to remove any residual nitrogen oxide, the product nitric acid from the bottom of the absorption tower is bleached with air before being sent to the Ammonium Nitrate Plant.

Tail gases from the absorption tower are preheated, treated in a Selective Catalytic Reduction reactor to abate NO_X content by injection of Ammonia over a catalyst bed, and then sent through the tail gas turbine before being released in the atmosphere.

1.1.4. Ammonium Nitrate plant

Ammonium nitrate is obtained by neutralization of nitric acid with gaseous ammonia according to the following reaction:

$$HNO_3 + NH_3 \rightarrow NH_4NO_3 + \text{heat}$$

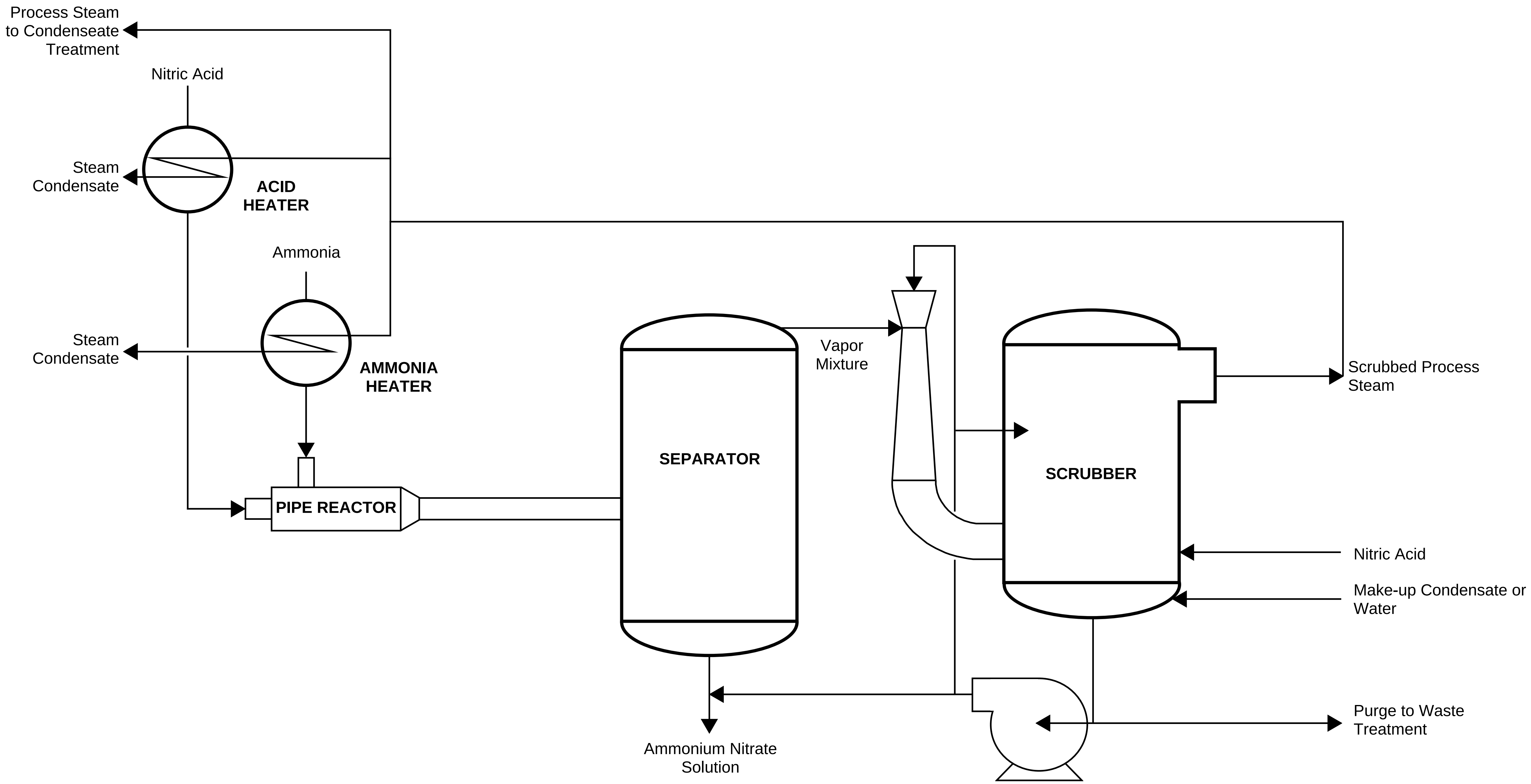
Depending on the licensor, the reaction can be accomplished in different type of reactors, such as one/two stage neutralizers at vacuum/atmospheric/elevated pressure (up to 5 Bar(g)) or pipe reactors. In all cases the reaction occurs directly, rapidly and exothermically.

Typical generic process schemes of the pipe reactor technology and AN granulation are illustrated in the following pages.

The heat produced inside the reactor can be employed directly or to generate low pressure steam.
In the first option, reaction heat is used directly inside the reactor to drive water off the AN solution; in this way it is possible to reach high concentrations, such as 97% AN, in the solution leaving the neutralizer. The flash steam can be employed for further concentration and reactants pre-heating.
In the second option, reaction heat is used to generate low pressure steam for other site uses, while solution concentration can be achieved with imported medium pressure steam, if needed.

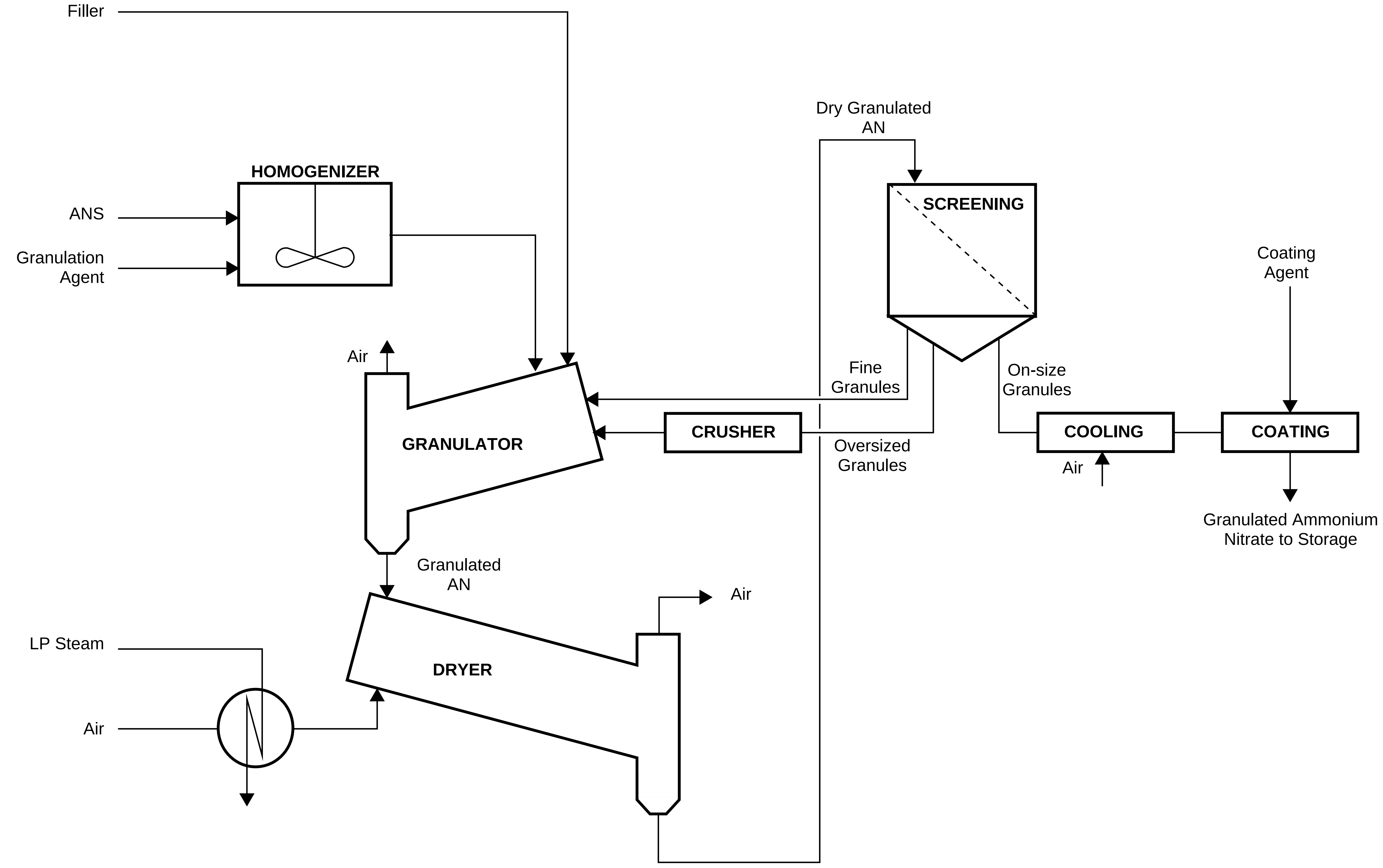
It is important to maintain the pH of the solution above 4.5, since low pH ammonium nitrate solutions are unstable and explosive.

Vapours generated in evaporators are treated in a scrubbing column to recover the nitric acid and the ammonium nitrate condensate.



SCHEMATIC BLOCK FLOW DIAGRAM

AMMONIUM NITRATE SYNTHESIS PLANT
PIPE REACTOR NEUTRALIZATION



SCHEMATIC BLOCK FLOW DIAGRAM

AMMONIUM NITRATE GRANULATION PLANT

A direct heat utilization technology, such as the pipe reactor, can be considered for the present case, as it represents a relatively simple solution for achieving high product concentration, allowing both UAN production and AN granulation without further concentration of the ANS leaving the separator.

In case of upset in the Urea or UAN Plant, it should be possible to produce solid ammonium nitrate in a granulation plant.

Rotary drum granulators produce solid particles by spraying the concentrated liquid AN into a long cylindrical rotating drum containing fine AN solid particles. The melt coats the seed particles with successive layers to form granules. The granules are dried and passed through a screen, where the larger particles are crushed, mixed with the fine ones, and used as seed particles in the granulator.

Inorganic salts like magnesium nitrate ($MgNO_3$) or magnesium oxide (Mg_2O) can be added to the AN melt to improve the physical characteristics of the final product and hinder the disintegration of granules due to thermal cycling.

Pure AN production is prohibited in some countries due to the safety issues that may arise during transportation, and due to its potential use in improvised explosive devices. Therefore, organic salts like limestone or dolomite can be added during the solidification process to obtain CAN (Calcium Ammonium Nitrate), which is a safer commercial product. The solidification process is the same used for AN granulation, but additional evaporation may be required.

1.1.5. UAN plant

Urea Ammonium Nitrate (UAN) is a liquid fertilized obtained from a mixture of urea solution, AN solution and water. The relevant quantities for UAN with 32% nitrogen content are AN 45% urea 35% and water 20%.

A small stream of nitric acid (~0.5%wt.) can be added to the mixture to neutralize possible ammonia slip in the urea solution stream.

UAN can be produced both in batch and continuous process.
In the batch process the components are weighed and mixed in a stirring tank, while in the continuous process, the streams of AN solution, urea and water are mixed in a static mixer (typically a small diameter baffled column).

The warm UAN is cooled and a small quantity of corrosion inhibitor is added before being pumped to storage tanks.

A typical scheme of the batch process is illustrated in the following pages.

1.1.6. Steam and BFW system

The steam and BFW system mainly include the following sub-systems.

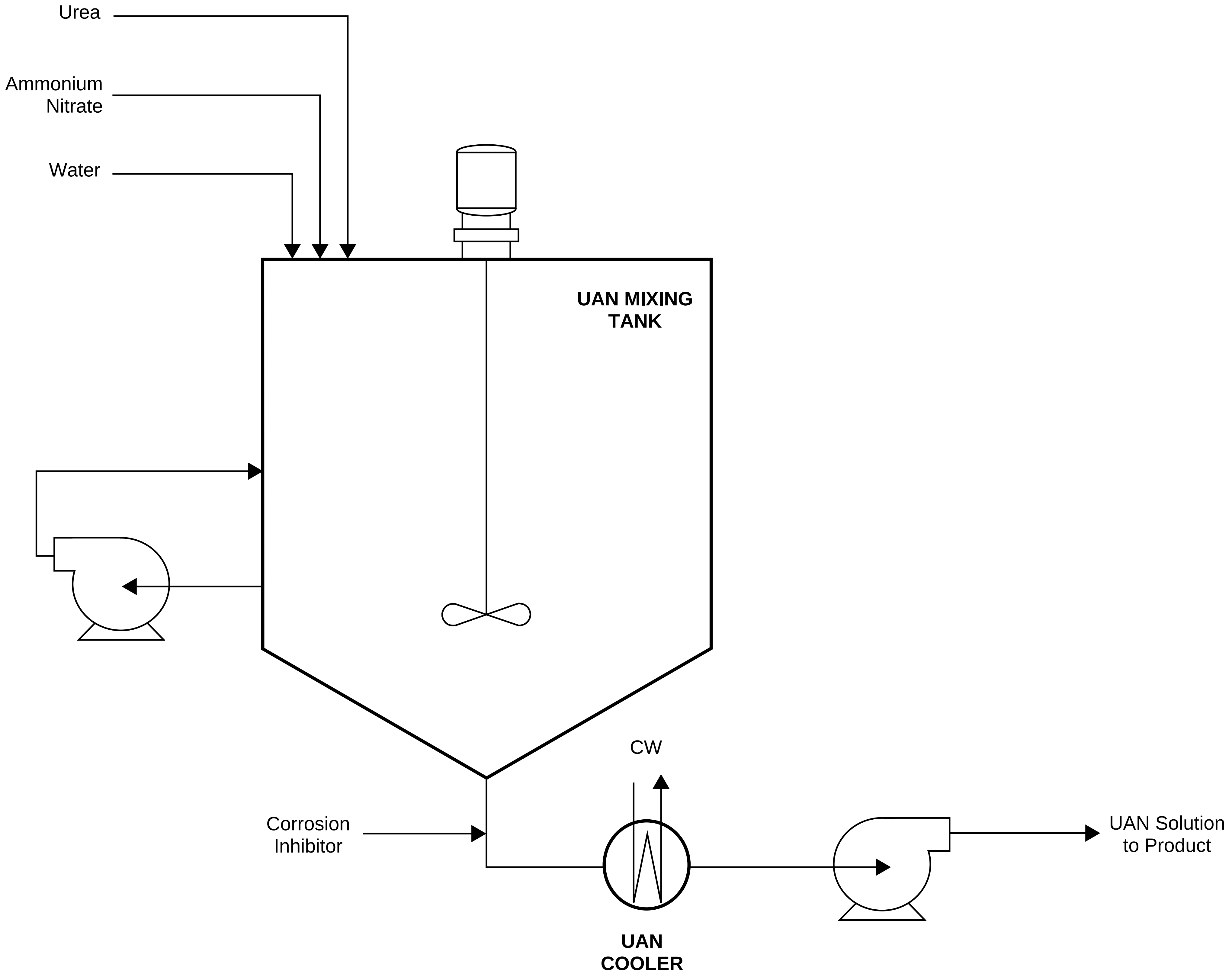
- Condensate Polishing Unit receives the process condensate from the Ammonia, Urea, Nitric Acid and Ammonium Nitrate Plants, after being stripped in their dedicated sections.

- Deaeration System receives the condensate from the Polishing Unit and the demineralized make-up water from the demi plant. LP steam from the main LP steam header is used as degassing agent. The Deaerator vent, consisting mainly of steam, is discharged to the atmosphere.

- HP Steam System includes the HP BFW pumps, HP steam drum and superheated steam header. The equipment required for BFW pre-heating and steam generation are included in the process unit of the syngas generation, ammonia synthesis and nitric acid synthesis. In the ammonia plant, the HP steam from the steam header, at about 12.0 MPa and 510°C, is typically fed to the steam turbine driver of the ammonia syngas compressor. To balance the MP steam requirements of the plant, some of the MP steam is extracted from the steam turbine and is sent to the MP header. HP steam produced in the Nitric Acid Plant is usually expanded in the HP steam turbine driving the air compressor and the NOx gas compressor.

- The MP steam from the steam header, typically at about 4.2 MPa and 375°C, is used as process steam in the ammonia plant and Urea Plant (i.e. hydrolyser, granulator, stripper). MP steam is also fed to the various steam turbine drivers of the process air compressor, ammonia refrigeration compressor, CO_2 compressor of the Urea Plant, SMR air and flue gas fan and BFW pumps. Exhaust LP steam from the various steam turbine drivers (back-pressure type) are collected and sent to the LP steam header at 0.6 MPa and 177 °C. This is to be used by the different LP consumers within the process sections.

- Steam Condensate System, which includes the MP and LP headers and drums, recovers the condensate from the different steam users within the plant. Steam released in the MP condensate and LP condensate flash drums are recovered and sent to the LP steam header and to the deaerator. The liquid condensates collected from the flash drums of steam headers and the condensate collected from the condensers of the different steam turbine drivers are sent to the condensate polishing unit.



SCHEMATIC BLOCK FLOW DIAGRAM

BATCH PRODUCTION OF UAN

- Blowdown System, which includes the blowdown drum, collects all the blow down steam from the MP and LP steam headers. The LP steam recovered from the blowdown drum is sent to the deaerator as part of the degassing agent; whilst the liquid effluent collected is sent to the wastewater treatment plant as effluent.

- Chemical Packages include chemicals for pH control, oxygen scavenger used in conditioning of the BFW in the Deaerator System, and phosphate injection package used in all the steam systems.

1.1.7. Seawater Desalination plant (Middle East case only)

Desalinated water is produced from sea water in a reverse-osmosis system.
The desalination plant is mainly composed by a clarification section, a filtration section, and the reverse-osmosis section.
Desalinated water is fed to the demi water plant to be further purified.

1.1.8. Demi Water Plant/Cooling Water System

The demi-water required for the steam production is produced by processing raw water using reverse-osmosis system followed by an electro-deionization system. The plant includes a raw water tank, a demi water tank, relevant pumps, and a potable water package and storage.

In the Middle East case, the Demi Water Plant does not include the reverse-osmosis process, which is carried out in the desalination plant.

Chemically treated demi water is also used as cooling water in a close circuit system (secondary system). This is mainly used for process coolers and for machinery cooling. The secondary cooling system is indirectly cooled by cooling towers fed with sea water.

Sea water in once through system (primary system) is used directly for the different steam turbine condensers and for the CO_2 compressor intercooler (only for the CO_2 capture case).

1.1.9. Balance of Plant (BoP)

The operation of the whole unit is supported by additional utilities and facilities such as:

- Instrument/Plant Air System
- Flare System
- Drain System
- Interconnecting
- Buildings (Control room, Electrical sub-station, Laboratory).

2. Case 2: Ammonia production from Natural Gas with Carbon Capture from SMR Flue Gas

2.1. Process Description

The overall Fertilizers plant configuration and material balance is identical to the one studied in Case 1, except for the capture and compression of CO_2 from the Primary Reformer's flue gas. Hence, the process descriptions and considerations reported in the previous Case shall also apply to the current one.

There are various technologies used for the CO_2 Capture and Compression that are commercially available. The process scheme selected for this study is generic, with no reference to specific licensor and equipment suppliers.

The process schemes of the CO_2 Capture and Compression Units are the same for all the four locations analysed.

2.1.1. *CO_2 Removal from the SMR Flue Gas (CO_2 Capture Case and Hybrid Case only)*

A generic chemical absorption technology featuring Amine-based solvent is considered for this study.

Since many licensed technologies make use of proprietary Amine-based solvents, Amine chemical composition is not specified for this study.

Calculation have been developed according to Wood internal database. A simplified approach has been followed: no amine emission or make up have been considered.

A typical Amine-based CO_2 Removal System consists of the flue gas quench cooler, CO_2 absorption section, heat exchanger network, CO_2 stripper and solvent purification section.

The flue gas of the primary SMR exiting the Combustion Air/Flue Gas Heat Exchanger with a temperature of about 155°C is initially fed to the quench cooler, where the flue gas is scrubbed with a caustic solution to reduce SOx down to around 1 ppm, thus minimizing solvent degradation. The flue gas is further cooled in a direct contact cooler using water wash.

Many Amine solvents might suffer from excessive degradation if the concentration of nitrogen dioxide (NO_2) in flue gases is too high. In such cases, it should be considered to pretreat the flue gas stream with an SCR Unit.

A blower is commonly installed to guarantee a stable flow of flue gas at the bottom of the Absorption tower.

The Absorption tower is generally a multi-level column which includes packed beds and a water wash section. As the flue gases rise through the column, CO_2 is absorbed by the descending solvent. CO_2 rich solvent is extracted from the bottom of the Absorption column and pumped to the top of the Solvent Regeneration column, while CO_2 lean solvent is pumped to the top of the Absorption column.

In order to improve the efficiency of the process, it is common practice to extract some of the heat generated by the absorption with cooling water in the middle section of the absorber.

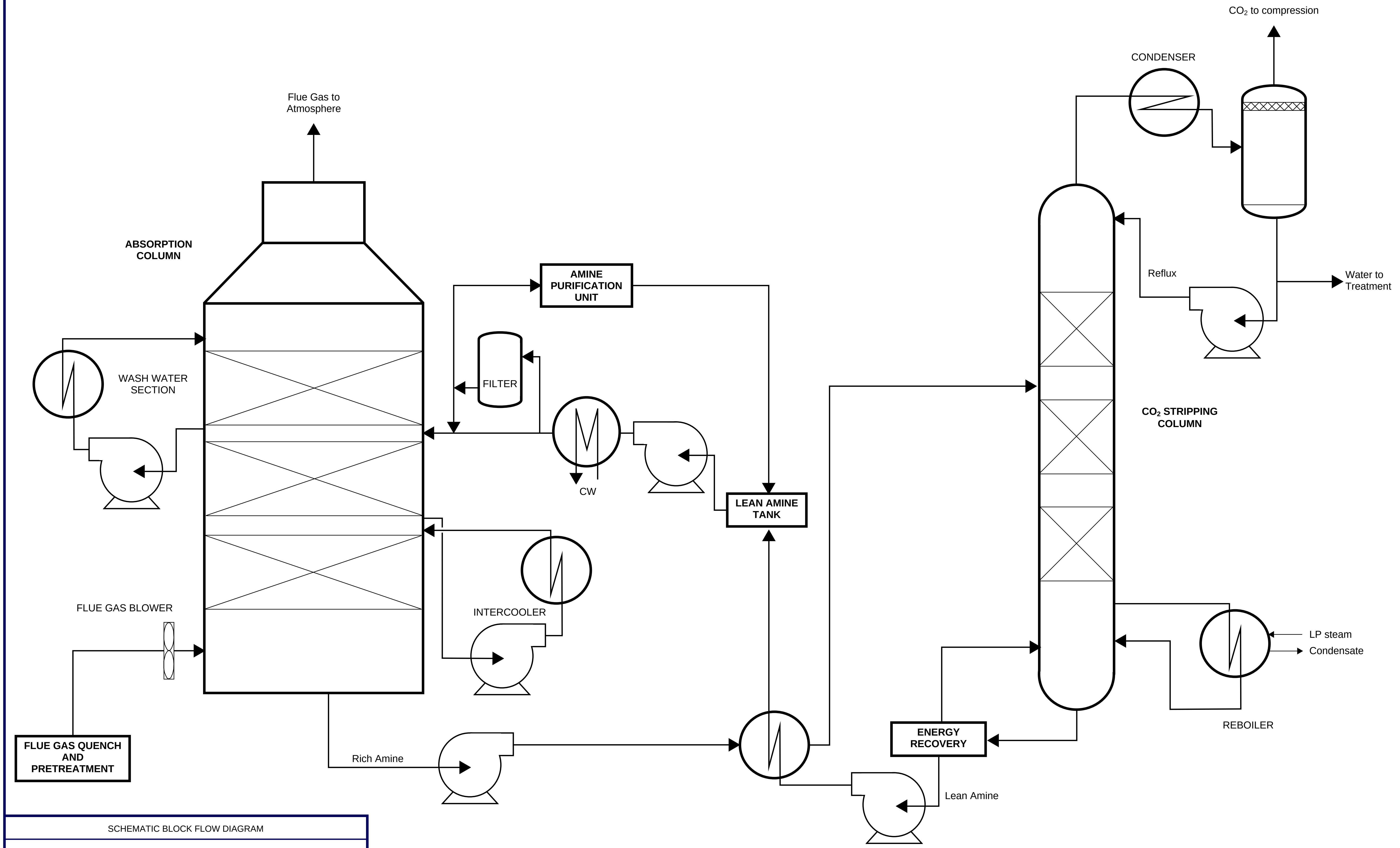
The flue gas leaving the packed beds is then scrubbed in the water wash section and passed through a demister section to remove any solvent particle and/or degradation by-products, and any entrained mist. Hence, the treated flue gas is released into the atmosphere.

Since colder temperatures are beneficial for the Absorption process, and a hotter solvent feed would decrease the reboiler duty of the Regeneration tower, different heat exchangers are usually employed to transfer heat from the lean to the rich solvent streams. Depending on the technology and licensor selected, many configurations for the heat exchangers between the Absorption and Regeneration columns are possible.

Rich amine stream is pumped to the top of the Regeneration column, where CO_2 is separated by stripping with a counter current flow of water vapor generated in the reboiler. Lean amine is drawn from the bottom of the column and pumped towards the Absorption column. The overhead gas, being composed mainly by CO_2 and water vapor, is partially condensed and passed through a separator, from which wet CO_2 is sent to compression, and steam condensate is in part refluxed and in part sent to treatment to be processed and recycled back to the Steam and BFW System of the plant.

Periodically some of the circulating solvent is sent to the purification section, in which thermal stable salts formed from reactions between amines and trace impurities are removed in a thermal reclaimer fed with MP steam. The heavy residues produced after every batch are collected and sent O.S.B.L. for disposal, while fresh solvent is added to replace the lost one.

A typical scheme for a CO_2 Capture Unit via Amine solvents is illustrated in the following pages.



SCHEMATIC BLOCK FLOW DIAGRAM

CO$_2$ ABSORPTION UNIT

2.1.2. CO$_2$ Compression and Dehydration (CO$_2$ Capture Case only)

The compression and dehydration unit includes the compressor, inter-stage coolers, knockout drums, dehydration package and dense phase CO$_2$ pump.

Wet CO$_2$ from the stripper's condenser is compressed to 8.0 MPa by using a single train eight-stage centrifugal compressor and then finally pumped to 11.0 MPa ready for transport.

The CO$_2$ compressor is an integrally geared and electrically driven machine. The compression system includes the associated equipment for anti-surge control, vent, inter-stage coolers, knockout drums and condensate draining facilities.

At the discharge of each compressor stage, CO$_2$ is cooled by seawater in an inter-stage cooler. Condensates are separated from the compressed gas and collected in the knockout drum. This is sent to the wastewater treatment plant.

After the sixth compression stage, the compressed gas is sent to the dehydration package unit. Drying is achieved by using solid desiccants. For this case, molecular sieve is considered. Other solid desiccants such as Activated Alumina or Silica Gel could also be used.

The dehydration unit consists of two parallel trains of 2-Bed Adsorbers producing dried CO$_2$ product with a dew point temperature of -40°C. In normal operation, half of the beds are kept in operation, while the others are regenerated by recycling a small stream (ca. 10%) of the dried product gas.

Final compression stages downstream the dehydration unit increase the product CO$_2$ pressure up to 8.0 MPa. After being cooled, dried CO$_2$ is in dense phase. This is then pumped and delivered to battery limits at the specified pipeline pressure of 11.0 MPa.

3. Case 3: Ammonia production from Natural Gas with Carbon Capture from SMR Flue Gas and Electrolysis

3.1. Process Description

In this case, hydrogen production from Natural Gas is integrated with hydrogen production from Water Electrolysis.
Hence, syngas from Syngas Plant is mixed with hydrogen from electrolysis, and the hydrogen enriched syngas is fed to the syngas compressor and sent to the Ammonia Synthesis Plant.

In order to determine the size of the process units it is necessary to specify some hypothesis:

- The capacity of all the process units downstream Ammonia Synthesis will be maintained identical to the previous cases, to facilitate any comparison.
- Feedstock CO_2 for Urea production is obtained from both the CO_2 captured from syngas and all the CO_2 captured from Steam Methane Reformer flue gas. As the target of Urea production remains the same, the capacity of the hydrogen production plant from fossil fuels is downsized accordingly. The balance of hydrogen to obtain 2000 MTPD of Ammonia is then produced via Water Electrolysis.
- The additional nitrogen required for the ammonia synthesis can be obtained in three main ways: via Air Separation Unit, via Pressure Swing Adsorption, or by feeding surplus air to the Auto Thermal Reformer. The comparison between these possibilities will be discussed in a dedicated section.

All the material streams downstream Ammonia Synthesis remain identical, except for the tail gases fed to SMR burner, which are reduced according with the lower quantity of inert gases entering the ammonia loop.

CO_2 captured from flue gas is fed directly to the compressor of the Urea Plant, therefore the compression and dehydration section is not present.

The steam turbine driven CO_2 compressor in the Urea Plant is substituted with an electric one, because less steam is produced in the Syngas Plant due to its smaller size.

Hydrogen quantity to be supplied via electrolysis should be around 50000 Nm^3/h.

The process scheme for the Electrolysis Unit is the same for all the four locations analysed.

3.1.1. *Water Electrolysis plant (Hybrid Natural Gas/Electrolysis Case only)*

Water Electrolysis is the electrochemical splitting of water molecules into hydrogen and oxygen by supplying electrical energy. The overall reaction is given by:

$$H_2O + \text{Electricity} \rightarrow H_2 + \tfrac{1}{2} O_2$$

Three main water electrolysis technologies can be identified basing on the applied electrolyte: Alkaline Electrolysis, Polymer Electrolyte Membrane Electrolysis and Solid Oxide Electrolysis.

For the present study it is considered to employ Alkaline Electrolysers, since it is the most mature technology among the three, and it has already been applied to large-scale plants with a size close to the current one (e.g. Aswan-Egypt Fertilizers plant in 1960, with a capacity > 40000 Nm^3_{H2}/h, 288 Electrolysers, P_{el} > 200 MW)[2].

Alkaline Electrolysers mainly consist of a series of electrodes immersed in a liquid electrolytic solution (usually a 25-30% aqueous KOH solution). Electrolyte is circulated in order to remove gaseous products and heat developed by reaction.

Typical generic process scheme of a single Electrolysis module is illustrated in the following pages.

The Electrolyser is powered by DC current, therefore a transformer and a rectifier are generally necessary.
The electrolyte system consists of two gas separators and the recirculation system. The electrolyte is separated from product gases, chilled, and recirculated to the cell block.

Typical operating conditions for Alkaline Electrolysers are 70-100°C and atmospheric pressure. Product oxygen can be either released to the atmosphere or stored and sold as byproduct. In the present study, the first alternative is considered.
Product hydrogen is furtherly treated in a water scrubber that removes any residual trace of the electrolyte, cools the stream and feeds water to the system. Hence, the hydrogen stream is compressed to Syngas pressure and sent to a deoxidizer, where Oxygen content can be reduced to ppm level so that it can be finally sent to Ammonia Synthesis Plant.

Since the quantity of hydrogen required from the electrolysis plant is far greater than the largest size available on the market, it is necessary to reach the target production by installing different modules in parallel.

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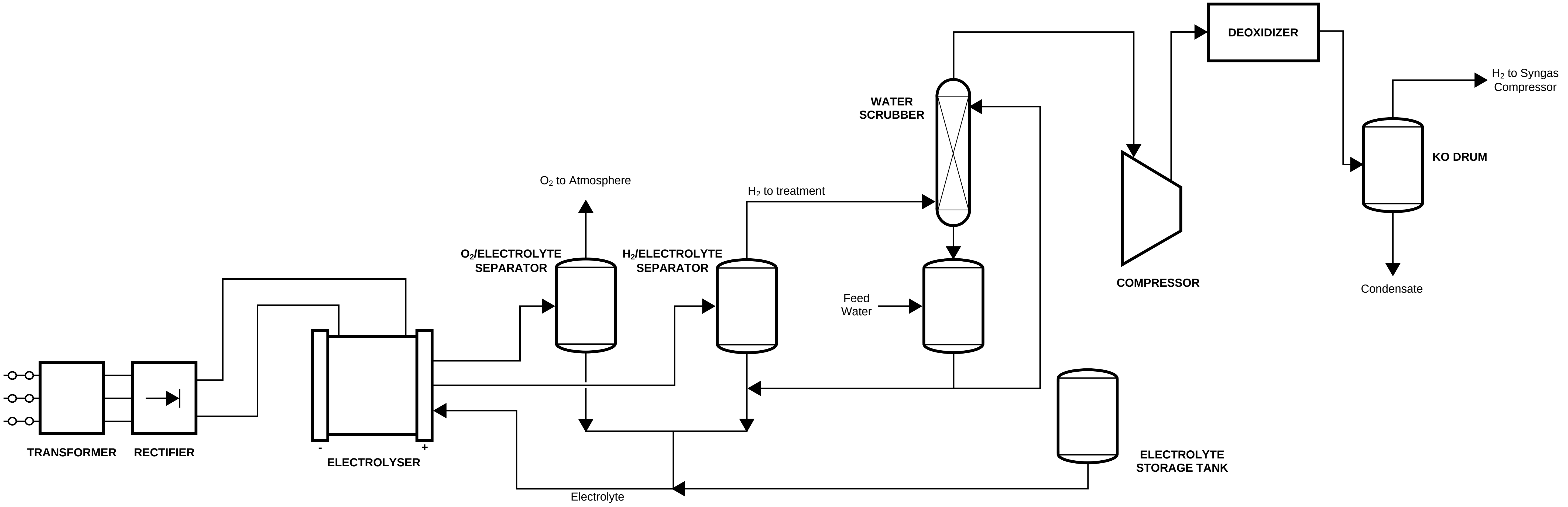
[2] Buttler A, Spliethoff H Current Status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review. Munchen; 2018.



SCHEMATIC BLOCK FLOW DIAGRAM

ELECTROLYSIS UNIT

For the present study, it has been considered to withdraw electricity from national grid. In cases where electricity is supplied by intermittent renewable sources, an energy storage solution should be adopted, such as batteries or hydrogen storage. In the latter case, PEM Electrolysers should be considered, due to their faster start-up time.

3.1.1. *Nitrogen supply (Hybrid Natural Gas/Electrolysis Case only)*

In the two previous cases, all the nitrogen reacting in the Ammonia Synthesis Loop was introduced with air in the autothermal reformer. In the current case, the Syngas Plant from Natural Gas is downsized, and therefore some nitrogen needs to be added to the process.

As stated before, three main options have been identified:

- Nitrogen production with Air Separation Unit (cryogenic fractionation)
- Nitrogen production with Pressure Swing Adsorption
- Feeding surplus air to the Autothermal Reformer

Air Separation Unit
It consists of a plant in which air is progressively compressed and cooled to cryogenic temperatures, until it can be fractionated in a distillation column. It is a quite energy intensive process, which requires numerous equipment including different compressors.

Pressure Swing Adsorption
Each PSA Unit encloses an air compressor, two adsorbent beds working in parallel, and a nitrogen buffer. Compressed air alternatively pressurizes one of the two beds, while the other one is kept at atmospheric pressure. The pressurized bed adsorbs moisture, oxygen, and carbon dioxide from the air, producing an almost pure Nitrogen stream (oxygen can be reduced to ppm levels, but Argon cannot be separated). When the bed reaches saturation, the other one is brought into operation, and the saturated bed is depressurized, so that adsorbed gases are released to the atmosphere.

Feeding surplus air to the Autothermal Reformer
This solution foresees that all the nitrogen needed in the ammonia reaction is supplied with the air fed to the ATR. Since the Syngas Plant from Natural Gas is smaller than the two previous cases, but the quantity of air introduced remains approximatively the same (because Ammonia capacity remains 2000 MTPD), it is necessary to unbalance the reforming duty towards the ATR. This, in practice, results in a slightly lower fuel gas consumption in the SMR furnace.
Given that the quantity of air introduced in the ATR is fixed, and that the sum of the CO_2 captured from Syngas and SMR flue gases is fixed too, the flow rates of feedstock and fuel Natural Gas are optimized to minimize the consumption of fossil fuels.

Here below a comparison table between the three options is reported:

	ASU	**PSA**	**Surplus air feed to ATR**
NG feedstock [kg/h]	28635	28635	30315
NG fuel [kg/h]	11265	11265	9300
Tot NG consumption [kg/h]	39900	39900	39615
Air to ATR [kg/h]	70027	70027	99058
H_2 production from NG [Nm^3/h]	121493	121493	120121
H_2 production in SMR [Nm^3/h]	89798	89798	77916
H_2 production in ATR [Nm^3/h]	9431	9431	19510
CO_2 captured from syngas [kg/h]	73117	73117	77977
CO_2 captured from SMR flue gases [kg/h]	29088	29088	24228
CO_2 sent to Urea plant [kg/h]	102205	102205	102205
H_2 production from Electrolysis [Nm^3/h]	48669	48669	50041
P_{EL} Electrolyzer [MW]	243	243	250
N_2 Production [Nm^3/h]	17088	17088	-
P_{EL} N_2 production [MW]	5.4	8.8	-

As regards the configuration of the Syngas plant, the case employing ASU is identical to the one employing PSA, while feeding surplus air to the ATR results in a slightly lower Natural Gas consumption, and in a reduction in the overall hydrogen production from Natural Gas, which implies a small increase in the capacity of the electrolysis plant.

The option with surplus air fed to the ATR is chosen for the current project because it demands lower fossil fuel consumption, and because it is the easiest solution to integrate hydrogen production from water Electrolysis in a traditional fertilizers plant.

2.4 TASK 1 – PLANT & ENVIRONMENTAL PERFORMANCE

Client	:	IEAGHG
Project Name	:	Achieving Deep Decarbonization in Worldwide Fertilizer Production
Document Name	:	Plant & Environment performance
Wood contract	:	1-BD-1160A

ISSUED BY	:	N. Marzorati
CHECKED BY	:	G. Collodi – A. Fontanella
APPROVED BY	:	G. Collodi

Date	Revised Pages	Issued by	Checked by	Approved by
16/12/2020				

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1. Environmental Performance Data

In this section the environmental impact of the plant is studied, with a focus on the CO_2 emissions.

The tables below include a breakdown of the CO_2 balance of the overall fertilizer complex for each of the analyzed locations.

1.1. UK

	EQUIVALENT FLOW OF CO_2 kmol/h	**EQUIVALENT FLOW OF CO_2 kmol/h**	**EQUIVALENT FLOW OF CO_2 kmol/h**
	Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INPUT STREAMS			
Natural gas feedstock	2410	2410	1825
Natural gas fuel	948	948	560
TOTAL	**3358**	**3358**	**2384**
OUTPUT STREAMS			
Total carbon in Urea product	2199	2199	2199
Total carbon in UAN product	126	126	126
CO_2 to storage	-	924	-
SUB-TOTAL (Carbon Not Emitted)	**2325**	**3250**	**2325**
Flue gas to stack	1033	108	59
Vents	-	-	-
Emission (A)	1033	108	59
TOTAL (OUT)	**3358**	**3358**	**2384**
Equivalent CO_2 in Urea product (%)	65.5%	65.5%	92.2%
Equivalent CO_2 in UAN product (%)	3.8%	3.8%	5.3%
Capture Rate - Capture from Flue Gas (%)	-	90.0%	90.0%
Captured CO_2 to Storage (%)	-	27.5%	-
AMOUNT OF CARBON NOT EMITTED (%)	**69.2%**	**96.8%**	**97.5%**
Indirect CO_2 Emission (B)[1]	611	639	2778
TOTAL CO_2 EMISSION (A) + (B)	**1644**	**747**	**2837**

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[1] Indirect CO_2 Emission is a result obtained in Task 3

1.2. Norway

	EQUIVALENT FLOW OF CO_2 kmol/h	**EQUIVALENT FLOW OF CO_2 kmol/h**	**EQUIVALENT FLOW OF CO_2 kmol/h**
	Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INPUT STREAMS			
Natural gas feedstock	2410	2410	1825
Natural gas fuel	948	948	560
TOTAL	**3358**	**3358**	**2384**
OUTPUT STREAMS			
Total carbon in Urea product	2199	2199	2199
Total carbon in UAN product	126	126	126
CO_2 to storage	-	924	-
SUB-TOTAL (Carbon Not Emitted)	**2325**	**3250**	**2325**
Flue gas to stack	1033	108	59
Vents	-	-	-
Emission (A)	1033	108	59
TOTAL (OUT)	**3358**	**3358**	**2384**
Equivalent CO_2 in Urea product (%)	65.5%	65.5%	92.2%
Equivalent CO_2 in UAN product (%)	3.8%	3.8%	5.3%
Capture Rate - Capture from Flue Gas (%)	-	90.0%	90.0%
Captured CO_2 to Storage (%)	-	27.5%	-
AMOUNT OF CARBON NOT EMITTED (%)	**69.2%**	**96.8%**	**97.5%**
Indirect CO_2 Emission (B)[2]	315	296	333
TOTAL CO_2 EMISSION (A) + (B)	**1348**	**404**	**392**

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[2] Indirect CO_2 Emission is a result obtained in Task 3

1.3. US

	EQUIVALENT FLOW OF CO_2 kmol/h	**EQUIVALENT FLOW OF CO_2 kmol/h**	**EQUIVALENT FLOW OF CO_2 kmol/h**
	Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INPUT STREAMS			
Natural gas feedstock	2410	2410	1825
Natural gas fuel	948	948	560
TOTAL	**3358**	**3358**	**2384**
OUTPUT STREAMS			
Total carbon in Urea product	2199	2199	2199
Total carbon in UAN product	126	126	126
CO_2 to storage	-	924	-
SUB-TOTAL (Carbon Not Emitted)	**2325**	**3250**	**2325**
Flue gas to stack	1033	108	59
Vents	-	-	-
Emission (A)	1033	108	59
TOTAL (OUT)	**3358**	**3358**	**2384**
Equivalent CO_2 in Urea product (%)	65.5%	65.5%	92.2%
Equivalent CO_2 in UAN product (%)	3.8%	3.8%	5.3%
Capture Rate - Capture from Flue Gas (%)	-	90.0%	90.0%
Captured CO_2 to Storage (%)	-	27.5%	-
AMOUNT OF CARBON NOT EMITTED (%)	**69.2%**	**96.8%**	**97.5%**
Indirect CO_2 Emission (B)[3]	1167	1222	4355
TOTAL CO_2 EMISSION (A) + (B)	**2200**	**1330**	**4414**

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[3] Indirect CO_2 Emission is a result obtained in Task 3

1.4. Middle East

	EQUIVALENT FLOW OF CO_2 kmol/h	EQUIVALENT FLOW OF CO_2 kmol/h	EQUIVALENT FLOW OF CO_2 kmol/h
	Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INPUT STREAMS			
Natural gas feedstock	2410	2410	1825
Natural gas fuel	948	948	560
TOTAL	**3358**	**3358**	**2384**
OUTPUT STREAMS			
Total carbon in Urea product	2199	2199	2199
Total carbon in UAN product	126	126	126
CO_2 to storage	-	924	-
SUB-TOTAL (Carbon Not Emitted)	**2325**	**3250**	**2325**
Flue gas to stack	1033	108	59
Vents	-	-	-
Emission (A)	1033	108	59
TOTAL (OUT)	**3358**	**3358**	**2384**
Equivalent CO_2 in Urea product (%)	65.5%	65.5%	92.2%
Equivalent CO_2 in UAN product (%)	3.8%	3.8%	5.3%
Capture Rate - Capture from Flue Gas (%)	-	90.0%	90.0%
Captured CO_2 to Storage (%)	-	27.5%	-
AMOUNT OF CARBON NOT EMITTED (%)	**69.2%**	**96.8%**	**97.5%**
Indirect CO_2 Emission (B) [4]	1341	1461	7360
TOTAL CO_2 EMISSION (A) + (B)	**2374**	**1569**	**7419**

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[4] Indirect CO_2 Emission is a result obtained in Task 3

2. Plant Performance Data

The tables below summarize the productions/consumptions and CO_2 emissions relevant to the overall fertilizer complex for each location.

Plant Performance Data				
UK		Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-18.67	-19.69	-18.84
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-6.60	-6.60	-6.60
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.23	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	34.21	39.47	300.45
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**
SPECIFIC EMISSIONS				
Specific CO_2 Emission to Urea Product (Direct)	tCO_2/tUrea	0.31	0.03	0.02
Specific CO2 Emission to UAN Product (Direct)	tCO2/tUAN	0.21	0.02	0.01
Specific CO_2 Captured to Urea Product	tCO2/tUrea	NA	0.28	0.74
Specific CO_2 Captured to UAN Product	tCO2/tUAN	NA	0.19	0.51
Equivalent CO_2 in Urea Product		65.5%	65.5%	92.2%
Equivalent CO_2 in UAN		3.8%	3.8%	5.3%
Equivalent CO_2 Captured to Storage		NA	27.5%	NA

Plant Performance Data

Norway		Natural Gas case without CCS	Natural Gas case with CCS	Hybrid Natural Gas/Electrolysis case with CCS
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-18.52	-19.55	-18.69
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-6.60	-6.60	-6.60
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.22	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	34.06	39.32	300.31
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**
SPECIFIC EMISSIONS				
Specific CO_2 Emission to Urea Product (Direct)	tCO_2/tUrea	0.31	0.03	0.02
Specific CO2 Emission to UAN Product (Direct)	tCO2/tUAN	0.21	0.02	0.01
Specific CO_2 Captured to Urea Product	tCO2/tUrea	NA	0.28	0.74
Specific CO_2 Captured to UAN Product	tCO2/tUAN	NA	0.19	0.51
Equivalent CO_2 in Urea Product		65.5%	65.5%	92.2%
Equivalent CO_2 in UAN		3.8%	3.8%	5.3%
Equivalent CO_2 Captured to Storage		NA	27.5%	NA

Plant Performance Data				
US		**Natural Gas case without CCS**	**Natural Gas case with CCS**	**Hybrid Natural Gas/Electrolysis case with CCS**
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-18.71	-19.74	-18.88
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-6.60	-6.60	-6.60
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.27	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	34.26	39.56	300.50
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**
SPECIFIC EMISSIONS				
Specific CO_2 Emission to Urea Product (Direct)	tCO_2/tUrea	0.31	0.03	0.02
Specific CO2 Emission to UAN Product (Direct)	tCO2/tUAN	0.21	0.02	0.01
Specific CO_2 Captured to Urea Product	tCO2/tUrea	NA	0.28	0.74
Specific CO_2 Captured to UAN Product	tCO2/tUAN	NA	0.19	0.51
Equivalent CO_2 in Urea Product		65.5%	65.5%	92.2%
Equivalent CO_2 in UAN		3.8%	3.8%	5.3%
Equivalent CO_2 Captured to Storage		NA	27.5%	NA

Plant Performance Data				
Middle East		**Natural Gas case without CCS**	**Natural Gas case with CCS**	**Hybrid Natural Gas/Electrolysis case with CCS**
INLET STREAMS				
Natural Gas (Feedstock)	t/h	40.03	40.03	30.31
Natural Gas (Fuel)	t/h	15.75	15.75	9.30
Natural Gas (Total Consumption)	**t/h**	**55.78**	**55.78**	**39.61**
Natural Gas LHV	MJ/kg	46.50	46.50	46.50
Total Energy Input	**MW**	**720.51**	**720.51**	**511.71**
OUTLET STREAMS				
Urea Product to BL	t/d	3166.83	3166.83	3166.83
	t/h	131.95	131.95	131.95
UAN Product to BL	t/d	520.88	520.88	520.88
	t/h	21.70	21.70	21.70
POWER BALANCE				
Ammonia Plant	MWe	-19.43	-20.45	-19.61
Urea Synthesis Plant	MWe	-2.93	-2.93	-18.30
Urea Granulation Plant	MWe	-4.62	-4.62	-4.62
Nitric Acid Plant	MWe	-0.08	-0.08	-0.08
Ammonium Nitrate Plant	MWe	-0.03	-0.03	-0.03
UAN Plant	MWe	-0.01	-0.01	-0.01
Steam + BFW System	MWe	-1.28	-1.28	-1.17
Utilities + BoP	MWe	-8.24	-8.20	-8.45
CO2 Capture Plant	MWe	NA	-1.01	-0.60
CO2 Compression and Dehydration Unit	MWe	NA	-3.40	NA
Electrolysis Plant	MWe	NA	NA	-250.21
Power imported from the grid	MWe	36.61	42.01	303.07
SPECIFIC CONSUMPTIONS				
Natural Gas (Feedstock) to Urea product	GJ/t Urea	12.67	12.67	9.59
Natural Gas (Fuel) to Urea product	GJ/t Urea	4.98	4.98	2.94
Feed + Fuel to Urea product	**GJ/t Urea**	**17.65**	**17.65**	**12.53**
Natural Gas (Feedstock) to UAN product	GJ/t UAN	8.77	8.77	6.64
Natural Gas (Fuel) to UAN product	GJ/t UAN	3.45	3.45	2.04
Feed + Fuel to UAN product	**GJ/t UAN**	**12.21**	**12.21**	**8.67**
SPECIFIC EMISSIONS				
Specific CO_2 Emission to Urea Product (Direct)	tCO_2/tUrea	0.31	0.03	0.02
Specific CO2 Emission to UAN Product (Direct)	tCO2/tUAN	0.21	0.02	0.01
Specific CO_2 Captured to Urea Product	tCO2/tUrea	NA	0.28	0.74
Specific CO_2 Captured to UAN Product	tCO2/tUAN	NA	0.19	0.51
Equivalent CO_2 in Urea Product		65.5%	65.5%	92.2%
Equivalent CO_2 in UAN		3.8%	3.8%	5.3%
Equivalent CO_2 Captured to Storage		NA	27.5%	NA

2.5 TASK 1 – PRELIMINARY UTILITY CONSUMPTION

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME: IEAGHG	Natural Gas case without CO_2 capture	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME: ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM	NM		1
FWI CONTRACT: 1BD1160A		CHKD	GC	GC		OF
LOCATION: UK		DATE	29/07/2020	18/08/2020		1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		18'667				325.0					11	12'396	7	4'331	172	400	500
			-0.4	-106.6			-4.2	-57.4	-156.4								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	202			
				-5.0				-2.5	-3.1								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		6'600								273.48				1'564		200	500
								-236.9	-36.6							-600	-1000
TOTAL		34'208	0	0	0	0	-12.5	-260.9	0	273.5	-	23'691	-	6'096	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

			REV.	REV. 0	REV. 1	REV. 2	SHEET
CUSTOMER NAME:	IEAGHG	Natural Gas case without CO_2 capture	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM	NM		1
FWI CONTRACT:	1BD1160A		CHKD	GC	GC		OF
LOCATION:	Norway		DATE	29/07/2020	18/08/2020		1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		18'524				325.0					11	12'396	7	4'323	172	400	500
			-0.4	-106.6			-4.2	-57.4	-156.5								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	198			
				-5.1				-2.5	-3.0								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		6'600								273.48				1'564		200	500
								-236.9	-36.6							-600	-1000
TOTAL		34'065	0	0	0	0	-12.5	-260.9	0	273.5	-	23'691	-	6'085	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME: IEAGHG	**Natural Gas case without CO_2 capture**	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME: ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM	NM		1
FWI CONTRACT: 1BD1160A		CHKD	GC	GC		OF
LOCATION: US		DATE	29/07/2020	18/08/2020		1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		LAKE WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		18'715				325.0					11	12'396	7	4'355	172	400	500
			-0.4	-106.6			-4.2	-57.4	-156.4								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	203			
				-5.0				-2.5	-3.1								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		6'600								273.48				1'564		200	500
								-236.9	-36.6							-600	-1000
TOTAL		34'255	0	0	0	0	-12.5	-260.9	0	273.5	-	23'691	-	6'122	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME: IEAGHG	**Natural Gas case without CO_2 capture**	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME: ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM	NM		1
FWI CONTRACT: 1BD1160A		CHKD	GC	GC		OF
LOCATION: Middle East		DATE	29/07/2020	18/08/2020		1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		19'430				325.0					11	12'396	7	4'440	172	400	500
			-0.4	-106.9			-4.2	-57.4	-156.1								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	220			
				-4.7				-2.5	-3.4								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		8'241								273.48				1'564		200	500
								-236.9	-36.6							-600	-1000
TOTAL		36'611	0	0	0	0	-12.5	-260.9	0	273.5	-	23'691	-	6'224	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

wood.

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME:	IEAGHG	Natural Gas case with CO_2 capture from SMR flue gas	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM			1
FWI CONTRACT:	1BD1160A		CHKD	GC			OF
LOCATION:	UK		DATE	18/08/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		19'689				325.0					11	12'396	7	4'331	172	400	500
			-47.2	-106.7			-4.2	-57.4	-109.5								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	202			
				-5.0				-2.5	-3.1								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO_2 CAPTURE		1'013	46.8	0.1				35.3			11	2'847					
									-82.2								
CO_2 COMPRESSION IN CO_2 CAPTURE PLANT		3'229									11	39	7	838			
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		6'600								267.1				1'754		200	500
								-265.8	-1.3							-600	-1000
TOTAL		39'472	0	0	0	0	-12.5	-254.5	0	267.1	-	26'578	-	7'124	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME:	IEAGHG	Natural Gas case with CO_2 capture from SMR flue gas	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM			1
FWI CONTRACT:	1BD1160A		CHKD	GC			OF
LOCATION:	Norway		DATE	18/08/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		19'546				325.0					11	12'396	7	4'323	172	400	500
			-47.2	-106.7			-4.2	-57.4	-109.6								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	198			
				-5.1				-2.5	-3.0								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO2 CAPTURE		1'013	46.8	0.1				35.3			11	2'847					
									-82.2								
CO_2 COMPRESSION IN CO_2 CAPTURE PLANT		3'219									11	39	7	838			
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		6'600								267.1				1'754		200	500
								-265.8	-1.3							-600	-1000
TOTAL		39'318	0	0	0	0	-12.5	-254.5	0	267.1	-	26'578	-	7'113	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME: IEAGHG
PROJECT NAME: ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION
FWI CONTRACT: 1BD1160A
LOCATION: US

Natural Gas case with CO_2 capture from SMR flue gas

REV.	REV. 0	REV. 1	REV. 2	SHEET
BY	NM			1
CHKD	GC			OF
DATE	18/08/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		LAKE WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		19'737				325.0					11	12'396	10	3'048	172	400	500
			-47.2	-106.8			-4.2	-57.4	-109.5								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	10	142			
				-5.0				-2.5	-3.1								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO_2 CAPTURE		1'013	46.8	0.1				35.3			11	2'847					
									-82.2								
CO_2 COMPRESSION IN CO_2 CAPTURE PLANT		3'272									11	39	10	587			
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		6'600								267.1				1'754		200	500
								-265.8	-1.3							-600	-1000
TOTAL		39'562	0	0	0	0	-12.5	-254.5	0	267.1	-	26'578	-	5'531	172.1	0	0

NOTES:
(1) DMW is the sum of DMW plus condensate from the process unit
(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses
(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME: IEAGHG
PROJECT NAME: ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION
FWI CONTRACT: 1BD1160A
LOCATION: Middle East

Natural Gas case with CO_2 capture from SMR flue gas

REV.	REV. 0	REV. 1	REV. 2	SHEET
BY	NM			1
CHKD	GC			OF
DATE	18/08/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		20'452				325.0					11	12'396	10	3'108	172	400	500
			-47.2	-107.0			-4.2	-57.4	-109.2								
UREA SYNTHESIS PLANT		2'930		111.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-140.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	10	154			
				-4.7				-2.5	-3.4								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO2 CAPTURE		1'013	46.8	0.1				35.3			11	2'847					
									-82.2								
CO_2 COMPRESSION IN CO_2 CAPTURE PLANT		3'401									11	39	10	587			
STEAM AND BFW PLANT		1'279							343.3								
						-332.7		-6.7	-3.8								
UTILITIES / BoP		8'202								267.1				1'754		200	500
								-265.8	-1.3							-600	-1000
TOTAL		42'009	0	0	0	0	-12.5	-254.5	0	267.1	-	26'578	-	5'603	172.1	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME:	IEAGHG	**HEAT AND MATERIAL BALANCE** **Hybrid Natural Gas/Electrolysis case with CO_2 capture**	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM			1
FWI CONTRACT:	1BD1160A		CHKD	GC			OF
LOCATION:	UK		DATE	14/09/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		18'836				254.5					11	11'032	7	4'331	122	400	500
			-28.2	-33.6			-2.9	-40.5	-149.2								
UREA SYNTHESIS PLANT		18'302		38.5				41.9			11	10'108					
			-2.6				-8.4	-2.3	-67.1								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	202			
				-5.0				-2.5	-3.1								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO_2 CAPTURE		603	27.9	0.1				12.5			11	1'696					
									-40.5								
ELECTROLYSIS PLANT		250'206							42.5		11	2'002					
								-42.5									
STEAM AND BFW PLANT		1'173							314.8								
						-262.2		-6.2	-46.4								
UTILITIES / BoP		6'600								308.2				1'718		200	500
								-260.2	-47.9							-600	-1000
TOTAL		300'452	0	0	0	0	-11.3	-296.9	0	308.2	-	26'025	-	6'250	122.2	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

(4) Cooling water to Electrolysis Plant can change with operating conditions

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME:	IEAGHG	**HEAT AND MATERIAL BALANCE** **Hybrid Natural Gas/Electrolysis case with CO_2 capture**	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM			1
FWI CONTRACT:	1BD1160A		CHKD	GC			OF
LOCATION:	Norway		DATE	14/09/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		18'691				254.5					11	11'032	7	4'323	122	400	500
			-28.2	-33.7			-2.9	-40.5	-149.1								
UREA SYNTHESIS PLANT		18'302		38.7				41.9			11	10'108					
			-2.6				-8.4	-2.3	-67.3								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	198			
				-5.1				-2.5	-3.0								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO_2 CAPTURE		603	27.9	0.1				12.5			11	1'696					
									-40.5								
ELECTROLYSIS PLANT		250'206							42.5		11	2'002					
								-42.5									
STEAM AND BFW PLANT		1'173							314.8								
						-262.2		-6.2	-46.4								
UTILITIES / BoP		6'600								308.2				1'718		200	500
								-260.2	-47.9							-600	-1000
TOTAL		300'307	0	0	0	0	-11.3	-296.9	0	308.2	-	26'025	-	6'239	122.2	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

(4) Cooling water to Electrolysis Plant can change with operating conditions

wood.

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME:	IEAGHG	**HEAT AND MATERIAL BALANCE** **Hybrid Natural Gas/Electrolysis case with CO_2 capture**	REV.	REV. 0	REV. 1	REV. 2	SHEET
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM			1
FWI CONTRACT:	1BD1160A		CHKD	GC			OF
LOCATION:	US		DATE	14/09/2020			1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		LAKE WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		18'884				254.5					11	11'032	7	4'355	122	400	500
			-28.2	-32.9			-2.9	-40.5	-149.9								
UREA SYNTHESIS PLANT		18'302		37.8				41.9			11	10'108					
			-2.6				-8.4	-2.3	-66.4								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	203			
				-5.0				-2.5	-3.1								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO_2 CAPTURE		603	27.9	0.1				12.5			11	1'696					
									-40.5								
ELECTROLYSIS PLANT		250'206							42.5		11	2'002					
								-42.5									
STEAM AND BFW PLANT		1'173							314.8								
						-262.2		-6.2	-46.4								
UTILITIES / BoP		6'600								308.2				1'718		200	500
								-260.2	-47.9							-600	-1000
TOTAL		300'500	0	0	0	0	-11.3	-296.9	0	308.2	-	26'025	-	6'276	122.2	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

(4) Cooling water to Electrolysis Plant can change with operating conditions

wood.

ESTIMATED UTILITY CONSUMPTIONS

CUSTOMER NAME:	IEAGHG	HEAT AND MATERIAL BALANCE Hybrid Natural Gas/Electrolysis case with CO_2 capture	REV.	REV. 0	REV. 1	REV. 2
PROJECT NAME:	ACHIEVING DEEP DECARBONIZATION IN WORLDWIDE FERTILIZER PROUCTION		BY	NM		
FWI CONTRACT:	1BD1160A		CHKD	GC		
LOCATION:	Middle East		DATE	14/09/2020		

SHEET 1 OF 1

	ELECTRIC POWER		STEAM t / h			BFW	EFFLUENT (3)	LOSSES (2)	DMW (1)	RAW WATER	SECONDARY COOLING WATER		SEA WATER		FUEL	INSTR. AIR	Nitrogen
	LOAD BHP	kW	LP	MP	HP	t/h	t/h	t/h	t/h	t/h	ΔT (°C)	m³/hr	ΔT (°C)	m³/hr	MMKcal/h	Nm^3/h	Nm^3/h
AMMONIA PLANT		19'608				254.5					11	11'032	7	4'440	122	400	500
			-28.2	-30.9			-2.9	-40.5	-151.9								
UREA SYNTHESIS PLANT		18'302		35.6				41.9			11	10'108					
			-2.6				-8.4	-2.3	-64.2								
UREA GRANULATION PLANT		4'618	2.6								11	156					
									-2.6								
NITRIC ACID PLANT		77	0.4			7.7			2.5		11	712	7	220			
				-4.7				-2.5	-3.4								
AMMONIUM NITRATE PLANT		29						4.4			11	222					
									-4.4								
UAN PLANT		8							1.3		11	97					
								-1.3									
CO_2 CAPTURE		603	27.9	0.1				12.5			11	1'696					
									-40.5								
ELECTROLYSIS PLANT		250'206							42.5		11	2'002					
								-42.5									
STEAM AND BFW PLANT		1'173							314.8								
						-262.2		-6.2	-46.4								
UTILITIES / BoP		8'449								308.2				1'718		200	500
								-260.2	-47.9							-600	-1000
TOTAL		303'072	0	0	0	0	-11.3	-296.9	0	308.2	-	26'025	-	6'378	122.2	0	0

NOTES:

(1) DMW is the sum of DMW plus condensate from the process unit

(2) Losses includes net water consumptions (-) and productions (+) in the reactions and steam/BFW system vent and steam losses

(3) Water effluent (to be sent to WWT) includes demi plant eluate, process condensate from process units and steam system blowdown

(4) Cooling water to Electrolysis Plant can change with operating conditions

3. TASK 2 – DEFINITION OF GOAL AND SCOPE FOR LIFE CYCLE ASSESSMENT (LCA)

Client	:	IEAGHG
Project Name	:	Feasibility Study on Achieving Deep Decarbonization in Worldwide Fertilizer Production
Document Name	:	Task 2 -Definition of goal and scope for the Life Cycle Assessment (LCA)
AmecFWI contract	:	1-BD-1160A

ISSUED BY : F. Corcelli
CHECKED BY : A. Fontanella
APPROVED BY : G. Collodi

Date	Revised Pages	Issued by	Checked by	Approved by
February 2021				

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1. Life cycle assessment (LCA)

Life cycle assessment or 'LCA' is a powerful tool to evaluate the environmental impact of a product, process, or service based on definition provide by the International Organization of Standardization (ISO). Through detailed accounting of the major emission sources enclosed in the life cycle of a product/process, the leading environmental contributors can be singled out, and one can take measures to reduce or eliminate their impact. ISO 14040 and ISO 14044 describing LCA methodology were implemented in the present study describing the four phases of LCA: 1) Goal and Scope definition; 2) Life Cycle Inventory (LCI); 3) Life Cycle Impact Assessment (LCIA); 4) Interpretation.

1.1. Goals and Scope definition

The goal of this study is to consider the life-cycle environmental footprint of different alternatives of producing **Urea** and **Urea Ammonium Nitrate** fertilizers, with and without CO_2 capture, in four different countries that are representative of certain regional conditions.

1.1.1. Intended applications and target audience

The aim of this study is to demonstrate how deep decarbonization of fertilizers' production can be achieved for regions such as Europe, North America, and Middle East. The findings of this study might begin the process of encouraging countries to consider multilaterally adoption of the least carbon intensive use and production of fertilizers.

The target audience of this LCA study are policy makers, the CCS technical community and the public to better understand the role and the value of CCS and its specific applications in different cases.

1.1.2. Functional Unit

The functional units (FU) of the study are represented by **1 tonne of Urea** and **1 tonne Urea Ammonium Nitrate (UAN)** produced in four different locations (UK, Norway, US and Middle East) and with three different technologies for ammonia precursor synthesis (from natural gas with and without CO_2 capture from Steam Methane Reformer–SMR flue gases and from partial water electrolysis).

1.1.3. System Boundaries

Four different locations are evaluated: **UK (England, South coast), Norway (Southwest coast), US (Midwest, Michigan lake coast), Middle East (Al-Jubayl, Saudi Arabia).**

For each case it is considered that the plant is situated at a greenfield, with no major site preparation required. There will be no restrictions on plant area and no special civil works or constraints on the delivery of equipment are assumed. Rail lines, roads, fresh water supply (except for Middle East) and high voltage electricity transmission lines, high pressure natural gas pipeline are considered available at plant battery limits.

The ammonia plant is designed to produce 2000 tonne/day of anhydrous ammonia. All the ammonia is used as feedstock for the Urea, Nitric Acid (NA) and Ammonium Nitrate (AN) plants.

The final products are **Urea** and **Urea Ammonium Nitrate** - UAN (32-0-0) solution.

For comparison reasons, the conventional ammonia production path (i.e. Haber-Bosch process with H_2 obtained from SMR and N_2 from compressed air to the secondary reformer) is used as benchmark, representing the state-of-the-art for ammonia synthesis. Moreover, the integration of CO_2 system capture from SMR flues gases as an alternative option for conventional ammonia synthesis path is also examined. In addition, ammonia production from hybrid natural gas/hydrogen obtained from water electrolysis (partial) is evaluated as a reference for a sustainable ammonia production routes. According to Wood estimation, in both case with CO_2 capture, a 90% CO_2 sequestration from SMR flue gases is foreseen.
The three investigated scenarios based on different ammonia production routes for each location are the following:

- **Case1: production of Ammonia from natural gas without CO_2 capture from SMR** (Steam Methane Reformer) **flue gases**;
- **Case2: production of Ammonia from natural gas with CO_2 capture from SMR flue gases;**
- **Case3:"hybrid" production of Ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases**.

System boundaries are **cradle-to-gate**, i.e. from resource extraction (cradle) to the factory gate (before final product it is transported to the consumer). The use phase and disposal phase of the product are omitted in this study.

The system boundaries for the base scenario are represented in the drawing below:

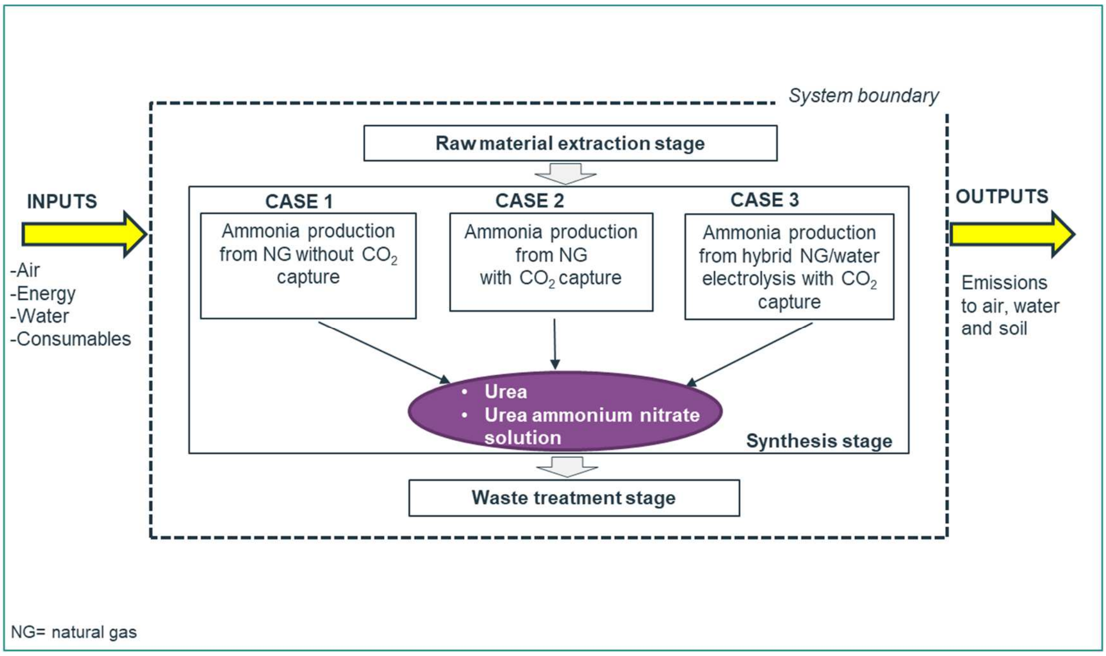

Figure 1. System boundaries of the LCA.

The overall production plant consists of the following units:

- Ammonia plant from methane includes:
  - Primary reformer (Feedstock Pre-treatment, (Pre-reformer) and SMR)
  - Secondary Reformer (ATR)
  - High and Low temperature CO Shift Conversion Section
  - Bulk CO_2 Removal Section
  - Methanation
  - Ammonia Synthesis and Refrigeration
  - Ammonia Storage
  - CO_2 Capture System from SMR flue gases (only for CO_2 capture scenario)
  - CO_2 Compression and Dehydration (only for CO_2 capture case)
- Electrolysis plant for hydrogen production (only for electrolysis case) includes:
  - Electrolytic cells
  - Hydrogen Purification and Compression
- Urea plant includes:
  - Urea Synthesis
  - Urea Solution Concentration
  - Granulation
  - Wastewater Treatment
- Nitric Acid plant includes:
  - NH_3 converter
  - Absorption column
- Ammonium Nitrate plant includes:
  - Neutralizer

    - Ammonium Nitrate Concentration
    - Granulation
- UAN plant includes:
    - Mixing
    - UAN tanks
- Steam and BFW plant
- Demi-Water Plant
- Sea Water Desalinization Plant (only for Middle East)
- Utilities and Balance of Plant (BoP), consisting of:
    - Cooling Water System
    - Flare System
    - Interconnecting
    - Drain System
    - Buildings (control Room, Laboratories, Electrical Sub-station)

For a complete description of the three production process, see Process Description document by Wood.

1.1.4. Main Assumption and Limitations

Main assumptions done in the study are:

- There are various technologies used in the production of ammonia, urea, nitric acid and ammonium nitrate that are commercially available. The process scheme selected for this study is generic, with no reference to specific licensor and equipment suppliers;
- The process scheme is the same for all the four locations analysed. The only exception is represented by the presence of a seawater desalination plant for the Middle East case;
- Natural gas, for what it concern process parameter definition, has fixed specification (composition, heating value and pressure at B.L.) in all cases as for IEA standards;
- Natural gas modelling, for what it concern environmental footprint evaluation, is country specific but dos not necessary match the fixed composition defined by IEA standards;
- Electricity is modelled according to country specific situation accounting for the current national grid, including net losses and imported electricity;
- In accordance with Davis & Haglund[1] (1999), it was assumed that urea synthesis took place at the same plant as ammonia (NH_3) production. CO_2 is produced as a by-product during NH_3-production, and is consequently used as input for the synthesis of urea (see also Althaus et al 2007)[2]. This CO_2 is released after the application in the field and has to be considered in the inventory for the agricultural production. Therefore, no CO_2 input to urea production has been modelled. CO_2 production impact is already accounted

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[1] Davis J. and Haglund C. 1999. The Swedish Institute for food and Biotechnology. SIK report N 654. Life Cycle Inventory of fertilizer production.

[2] Althaus H.J., Chudacoff M., Hischier R., Jungbluth N., Osses M. and Primas A, 2007. Life Cycle Inventories of Chemicals. Final report ecoinvent data v2 No.8 EMPA, Swiss Centre for Life Cycle Inventories, Dubendorf, CH.

for in ammonia plant. This CO_2 is released after the application in the field and has to be considered in the inventory for the agricultural production.

- Within investigated fertilizers' production the potential environmental burden from chemical solvent production used for CO_2 separation were not investigated due to lack of data.

1.1.5. *Data Quality Requirements*

The process scheme selected for this study is generic, with no reference to specific licensor and equipment suppliers. All process data are therefore engineering estimates and calculations based on Wood sectoral experience.

For this reason, no reference year has been defined.

While the process scheme is the same for all locations analysed, processes have been made country specific considering electricity mixes as supplied from national grids, natural gas from national distribution networks and regionalized water supply.

1.1.6. *Allocation Method*

When required, a mass allocation approach of plants data to products and co-products has been used. An economic allocation approach was used as sensitivity analysis applied to co-products ammonia and CO_2 (see 3.8 paragraph, Task 3).

4. TASK 3 – LCAs (INVENTORY, IMPACT ASSESSMENT AND INTERPRETATION) OF SELECTED PRODUCTION ROUTES PER REGION

Client	:	IEAGHG
Project Name	:	Feasibility Study on Achieving Deep Decarbonization in Worldwide Fertilizer Production
Document Name	:	Task 3 - LCAs (inventory, impact assessment and interpretation) of the selected production routes per region
AmecFWI contract	:	1-BD-1160A

ISSUED BY	:	F. Corcelli
CHECKED BY	:	A. Fontanella
APPROVED BY	:	G. Collodi

Date	Revised Pages	Issued by	Checked by	Approved by
February 2021				

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1. Life cycle Inventory (LCI)

The LCI phase consists of a compilation and quantification of inputs (consumption of materials and energy resources) and outputs (emissions to water, air and soil) that occur throughout the system under study. In the present study, the main design and modelling assumptions used in describing the proposed cases were provided by Wood's engineers. Bases of design process data, simulated with Aspen HYSYS v10 (by AspenTech) and used to evaluate the heat and material balance, were employed for the foreground system. It is noteworthy that data process can be considered representative of the most advanced technology in nitrogen fertilizers' production. Moreover, the design of the process and utility units are in general accordance with the main International and Local Standard Codes. Some data correlated to solid, liquid and gaseous emissions discharged from the plant are compliant with the standard limits required by the local directives currently in force (for more details please see "Bases of design" document by Wood).

Some background data, related to energy production, auxiliary materials and impacts of the waste management were modeled using the Ecoinvent 3.6 database predefined processes (Wernet et al., 2016) [1]. Ecoinvent is recognized as one of the most complete background LCI databases available, from a quantitative (number of included processes) and a qualitative (quality of the validation processes, data completeness, etc.) perspective. Generic datasets were used for modelling materials and chemicals, whilst for the supply of energy (electricity and natural gas) and water, specific datasets for each investigated location (i.e. UK, Norway, USA, Saudi Arabia) were selected.

Items not included in the system boundaries consist of: 1) construction and decommissioning of the plants; 2) repair and maintenance of equipment and machinery used in the process; 3) human activities; 4) non-predictable fugitive/accidental emissions. The system boundary incorporates all major processes within Urea and UAN solution synthesis. Urea and UAN solution were the main products while process raw material included water, CO_2, air and natural gas.

All inputs and outputs of the system under analysis have been first collected for the daily amount of Urea and UAN solution fertilizer produced and in the results interpretation phase have been referred to the selected functional units later. To facilitate the analysis, the studied system was divided into the most significant process units within the Urea and UAN synthesis (including intermediate products) and the data were grouped into different categories in life cycle inventory (LCI) tables. Life cycle inventories for the three examined cases are presented in tables 1:24 below. The source of each number has been defined as "calculation" for values obtained from calculations performed in Task 1, and as "literature" for values obtained from Wood internal database.

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[1] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, 21(9), pp.1218–1230.

Table 1. LCI inventory for ammonia plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Ammonia plant (Natural gas case without CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Ammonia liquid	tonnene/day	2,000	2,000	2,000	2,000	Used as feedstock for Urea and Nitric Acid synthesis.	Basis of Design
Byproduct							
CO_2	tonne/day	2,510	2,510	2,510	2,510	Fed to the Urea Plant as feedstock for Urea Synthesis Reaction.	Calculation
Steam to Urea Plant	tonne/day	2,558	2,557	2,559	2,565	Fed to the Urea Plant as utility steam.	Calculation
Steam to Nitric Acid plant	tonne/day	92	9.2	9.2	9.2	Fed to the Nitric Acid Plant as utility steam.	Calculation
Water to BFW plant (Utilities)	m^3/day	3,754	3,755	3,753	3,747	Water recovered from the process and utilities condensates, and sent to the BFW plant	Calculation
Resources							
Air	tonne/day	2,349	2,349	2,349	2,349	Feedstock for ammonia production.	Calculation
Water (cooling water)	m^3/day	103,932	103,742	104,516	106,564	Sea Water (lake water in case of US) heated by 7/10°C by primary cooling circuit.	Calculation

CASE 1. Ammonia plant (Natural gas case without CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water (boiler feedwater)	m^3/day	7,800	7,800	7,800	7,800	BFW is used both for utility steam production and for process steam. Utility steam is used for multiple purposes: some is expanded in turbine drivers and is recovered, some is exported to Urea plant. Process steam is fed to the steam reformer, and most of it reacts with hydrocarbons, while the rest is partially recovered.	Calculation
Materials/fuels							
Natural gas (as feedstock)	Sm^3/day	1,211,128	1,211,128	1,211,128	1,211,128	Used as feedstock for SMR.	Calculation
Natural gas (as fuel)	Sm^3/day	476,455	476,455	476,455	476,455	Used as fuel for heating SMR.	Calculation
Catalyst:							
Zinc Oxide based catalyst	m^3/day	0.36	0.36	0.36	0.36	This value is the daily consumption (24 h without interruption). This catalyst is used in desulfurizer reactor, and it is generally substituted once every 6 months.	Literature
Nickel based catalyst for primary reformer	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature
Nickel based catalyst for autothermal reformer	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature

CASE 1. Ammonia plant (Natural gas case without CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Iron based catalyst promoted by Chromium/Copper oxides	m^3/day	0.05	0.05	0.05	0.05	This value is the daily consumption (24 h without interruption). This catalyst is used in HT shift reactor, and it is generally substituted once every 4 years.	Literature
Copper based catalyst	m^3/day	0.06	0.06	0.06	0.06	This value is the daily consumption (24 h without interruption). This catalyst is used in LT shift reactor, and it is generally substituted once every 4 years.	Literature
Nickel based catalyst for methanator reactor	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature
Magnetite based catalyst	m^3/day	0.09	0.09	0.09	0.09	This value is the daily consumption (24 h without interruption). This catalyst is used in ammonia synthesis reactor, and it is generally substituted once every 4 years.	Literature
Solvent (aMDEA)	tonne/day	-	-	-	-	Not available, depends on licensor	
Electricity/heat							
Electricity	kWh/day	448,008	444,576	449,160	466,320	Covers all the electric demand of the ammonia plant. Input from external.	Calculation
Emissions to air							
O_2	kg/day	126,937	126,937	126,937	126,937		Calculation

CASE 1. Ammonia plant (Natural gas case without CO_2 capture)

	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
H_2O	kg/day	918,029	918,029	918,029	918,029		Calculation
NO_X	kg/day	< 619.5	< 619.5	< 619.5	< 619.5	Maximum value ensured by BAT, as stated in BoD.	Calculation
CO	kg/day	< 154.9	< 154.9	< 154.9	< 154.9	Maximum value ensured by BAT, as stated in BoD.	Calculation
CO2, fossil	kg/day	1,090,582	1,090,582	1,090,582	1,090,582		Calculation
SOX	kg/day	-	-	-	-	Negligible, since the feed gas contains only 5 ppm of sulphur, and it is further desulphurized.	
Heat	MJ/day	17,160,631	17,232,343	17,140,759	16,705,303	Heat from: -Flue gases -CW (mainly disposed of as latent heat in cooling tower)	Calculation
Emissions to water							
NH3 or NH4 (as N)	kg/day	-	-	-	-	Negligible.	Literature
Waste to treatment							
Wastewater	m^3/day	100	100	100	100	Sent to wastewater treatment.	Calculation
Spent catalyst	tonne/day	-	-	-	-	Usually the spent catalyst is collected from the catalyst vendor. It applies to all the catalysts cited in the previous rows.	
Spent solvent	tonne/day	-	-	-	-	Recovered.	Calculation

Table 2. LCI inventory for urea synthesis plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Urea Synthesis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Liquid Urea to granulation	tonne/day	3,167	3,167	3,167	3,167	Urea to granulation plant.	Calculation
Urea solution 77% to UAN plant.	tonne/day	235.6	235.6	235.6	235.6	Number indicates 77% Urea solution to UAN. (181.4 t/d of 100% Urea).	Calculation
Byproduct							
Water to BFW plant (Utilities)	m^3/day	3,365	3,365	3,365	3,365	Water recovered from the process and utilities condensates, and sent to the BFW plant.	Calculation
Steam to Urea granulation plant	tonne/day	63	63	63	63	LP Steam sent to Urea granulation plant	Calculation
Resources							
Steam	tonne/day	2,679	2,679	2,679	2,679	MP steam from Ammonia plant and Nitric Acid Plant.	Calculation
Materials/fuels							
Ammonia liquid	tonne/day	1,898	1,898	1,898	1,898	Feedstock for Urea production.	Calculation
CO_2	tonne/day	2,510	2,510	2,510	2,510	Feedstock for Urea production.	Calculation

CASE 1. Urea Synthesis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Electricity/heat							
Electricity	kWh/day	70,320	70,320	70,320	70,320	Electricity consumed in the synthesis plant.	Calculation
Emissions to air							
Heat	MJ/day	11,170,628	11,170,628	11,170,628	11,170,628	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Waste to treatment							
Wastewater	m^3/day	201	201	201	201	Sent to wastewater treatment.	Calculation

Table 3. LCI inventory for urea granulation plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Urea Granulation plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Urea granulate	tonne/day	3,167	3,167	3,167	3,167	Urea Product.	Calculation
Byproduct							

CASE 1. Urea Granulation plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water to BFW (Utilities)	m^3/day	63	63	63	63	Steam condensate sent back to BFW plant	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	Urea Plant only uses cooling water from a closed circuit.	Literature
Steam	tonne/day	63	63	63	63	LP steam from Urea synthesis plant.	Literature
Materials/fuels							
Formaldehyde	tonne/day	31.7	31.7	31.7	31.7	Granulation agent in Urea granulation plant.	Calculation
Electricity/heat							
Electricity	kWh/day	110,832	110,832	110,832	110,832	Electricity consumed in the granulation plant.	Literature
Emissions to air							
Ammonia	kg/day	106	106	106	106	From Granulation tower. Maximum value ensured by BAT, as stated in BoD.	Calculation
Particulates	kg/day	211	211	211	211	From Granulation tower. Maximum value ensured by BAT, as stated in BoD.	Calculation
Heat	MJ/day	172,333	172,333	172,333	172,333	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 4. LCI inventory for nitric acid plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Nitric Acid Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Nitric acid to ANS plant	tonne/day	303.8	303.8	303.8	303.8	Number indicates 60% NA solution. (182.3 t/d of 100% nitric acid). This stream is used as feedstock for ANS production.	Calculation
Nitric acid to UAN plant	tonne/day	4.4	4.4	4.4	4.4	Number indicates 60% NA solution. (2.6 t/d of 100% nitric acid). This stream is used to neutralize slipstreams of ammonia in UAN.	Calculation
Byproduct							
Steam	tonne/day	120.2	121.3	119.3	113.3	MP steam to Urea plant.	Calculation
Water to BFW plant (Utilities)	m^3/day	74.0	72.9	74.8	80.9	Water from turbine condensate.	Calculation
Resources							
Water (cooling water)	m^3/day	4,837.9	4,760.8	4,881.5	5,273.2	Sea Water (lake water in case of US) heated by 7/10°C by primary cooling circuit.	Calculation
Water (boiler feedwater)	m^3/day	184.9	184.9	184.9	184.9	Water used for steam production.	Calculation

CASE 1. Nitric Acid Plant

	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water (demineralized water)	m^3/day	61.0	61.0	61.0	61.0	Water used for process purpose (nitric oxides absorption).	Calculation
Steam	tonne/day	9.2	9.2	9.2	9.2	Utility steam from Ammonia plant.	Calculation
Materials/fuels							
Ammonia liquid	tonne/day	101.5	101.5	101.5	101.5	Feedstock for Nitric Acid production.	Calculation
Air	tonne/day	845.3	845.3	845.3	845.3	Feedstock for Nitric Acid production.	Calculation
Catalyst:							
Platinum/rhodium catalyst gauze	kg/day	0.16	0.16	0.16	0.16	This value is the daily consumption (24 h without interruption). It is generally substituted once every 70 days.	Literature
De_NOx catalyst	kg/day	-	-	-	-	Not available.	
Electricity/heat							
Electricity	kWh/day	1,849	1,849	1,849	1,849	Covers all the electric demand of the NA plant.	Calculation
Emissions to air							
Ammonia	kg/day	< 2.15	< 2.15	< 2.15	< 2.15	< 5 ppm. Maximum value ensured by BAT, as stated in BoD.	Literature

CASE 1. Nitric Acid Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Nitrogen oxides	kg/day	< 0.76	< 0.76	< 0.76	< 0.76	< 30 ppm. Maximum value ensured by BAT, as stated in BoD.	Literature
N_2O	kg/day	37	37	37	37	Maximum value ensured by BAT, as stated in BoD.	Literature
Platinum	g/day	6.1	6.1	6.1	6.1	Platinum vaporized from the catalyst gauze, and not recovered.	Literature
Water	kg/day	4,543	4,543	4,543	4,543		Literature
Heat	MJ/day	787,000	787,000	787,000	787,000	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Waste to treatment							
Spent catalyst	kg/day	-	-	-	-	Catalyst is substituted every 70 days. The spent catalyst is usually collected by vendor. 70% of vaporized Pt is recovered (14.2 g/day), 30% is lost (6.1 g/day).	Literature

Table 5. LCI inventory for ammonium nitrate plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Ammonium nitrate plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Ammonium nitrate solution to UAN	tonne/day	249.8	249.8	249.8	249.8	Number indicates 92.5% AN solution. (231 t/d of 100% ammonium nitrate)	Calculation
Byproduct							
Water to Demi water plant (Utilities)	tonne/day	104.7	104.7	104.7	104.7	Water obtained from process, sent back to Demi Water plant	Calculation
Resources							
Water (cooling water)	m3/day	-	-	-	-	ANS Plant only uses cooling water from a closed circuit.	
Materials/fuels							
Ammonia liquid	tonne/day	49.2	49.2	49.2	49.2	Feedstock for ANS production	Calculation
Nitric acid	tonne/day	303.8	303.8	303.8	303.8	Feedstock for ANS production (in a 60% solution)	Calculation
Limestone	ton/day	-	-	-	-	Not available. This chemical should be used only in case of upset of Urea /UAN plant to produce granulated AN	
Magnesium nitrate (MgNO3)	tonne/day	-	-	-	-	Not available. This chemical should be used only in case of upset of Urea /UAN plant to produce granulated AN	

CASE 1. Ammonium nitrate plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Electricity/heat							
Electricity	kWh/day	693.1	693.1	693.1	693.1	Covers all the electric demand of the ANS plant.	Calculation
Heat from natural gas	MJ/day	-	-	-	-	No heat from NG.	Literature
Emissions to air							
Heat	MJ/day	245,633	245,633	245,633	245,633	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 6. LCI inventory for urea ammonium nitrate solution (UAN 32-0-0) plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Urea ammonium nitrate solution (32-0-0) plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Urea ammonium nitrate solution (32-0-0)	tonne/day	520.9	520.9	520.9	520.9	UAN product	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	UAN Plant only uses cooling water from a closed circuit.	

Materials/fuels							
Urea 77% Solution	tonne/day	235.6	235.6	235.6	235.6	Feedstock for UAN	Calculation
Nitric acid 60% Solution	tonne/day	4.4	4.4	4.4	4.4	Feedstock for UAN	Calculation
Ammonium nitrate 92.5% solution	tonne/day	249.8	249.8	249.8	249.8	Feedstock for UAN	Calculation
Demineralized water	tonne/day	31.1	31.1	31.1	31.1	Feedstock for UAN	Calculation
Electricity/heat							
Electricity	kWh/day	182	182	182	182		Calculation
Emissions to air							
Heat	MJ/day	106,840	106,840	106,840	106,840	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 7. LCI inventory for utilities and balance of plant. Case 1 “Urea and UAN synthesis from natural gas without CO_2 capture”.

CASE 1. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
BFW to ammonia plant	m^3/day	7,800.0	7,800.0	7,800.0	7,800.0		Calculation
BFW to Nitric Acid plant	m^3/day	184.9	184.9	184.9	184.9		Calculation
Demi water to Nitric Acid plant	m^3/day	61.0	61.0	61.0	61.0		Calculation
Demi water to UAN plant	m^3/day	31.1	31.1	31.1	31.1		Calculation
Resources							

CASE 1. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water (cooling water)[2]	m^3/day	37,526.5	37,526.5	37,526.5	37,526.5	This is the sea water makeup to cooling tower (lake water for US) to cover the losses by evaporation/drift from the cooling tower (lost in the atmosphere).	Calculation
Water recovered from Ammonia Plant	m^3/day	3,754	3,755	3,753	3,747		Calculation
Water recovered from Urea Plant	m^3/day	3,365	3,365	3,365	3,365		Calculation
Water recovered from Urea Granulation Plant	m^3/day	63	63	63	63		Calculation
Water recovered from Nitric Acid Plant	m^3/day	74	73	75	81		Calculation
Water recovered from Ammonium Nitrate Plant	m^3/day	105	105	105	105		Calculation

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[2] In order to allocate this water consumption to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia plant (52.32%), urea synthesis plant (42.67%), urea granulation plant (0.66%), nitric acid plant (3.01%), ammonium nitrate plant (0.94%), UAN plant (0.41%).

CASE 1. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Makeup water[3]	m^3/day	6,563	6,563	6,563	6,563	This stream is the makeup water for the demi water and BFW plant. - Normally it is obtained by demineralization (and a little treatment for BFW) of raw water. - In the Middle East case it comes from sea water, which also needs to be desalinated, and hence it requires higher electric consumption.	Calculation
Electricity/heat							
Electricity[4]	kWh/day	189,093	189,093	189,093	228,474		Calculation
Emissions to air							

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[3] In order to allocate this water consumption to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia plant (71.34%), urea synthesis plant (24.5%), urea granulation plant (0.58%), nitric acid plant (2.33%), ammonium nitrate plant (0.94%), UAN plant (0.28%)

[4] In order to allocate this electricity consumption to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant, since it constitutes the larger part of the utilities energy demand. The percentage attributed to each plant is reported: ammonia plant (52.32%), urea synthesis plant (42.67%), urea granulation plant (0.66%), nitric acid plant (3.01%), ammonium nitrate plant (0.94%), UAN plant (0.41%).

CASE 1. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water (cooling water)[5]	m3/day	37,526.5	37,526.5	37,526.5	37,526.5	These are the sea water losses from the cooling tower (lake water for US) (evaporation/drift from the cooling tower) (lost in the atmosphere).	Calculation
Emissions to water							
Water losses from BFW and Demi water plant[6]	m^3/day	161.5	161.5	161.5	161.5	This is the water lost from the BFW and demi water plant because of leakage	Calculation

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[5] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia (52.32%), urea synthesis (42.67%), urea granulation (0.66%), nitric acid (3.01%), ammonium nitrate (0.94%), UAN (0.41%)

[6] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia (71.34%), urea synthesis (24.50%), urea granulation (0.58%), nitric acid (2.33%), ammonium nitrate (0.96%), UAN (0.28%).

CASE 1. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
CW losses from CW loop[7]	m^3/day	5,685.8	5,685.8	5,685.8	5,685.8	This is the Cooling Water lost from the CW closed loop because of leakage	Calculation

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[7] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (52.32%), urea synthesis plant (42.67%), urea granulation plant (0.66%), nitric acid plant (3.01%), ammonium nitrate plant (0.94%), UAN plant (0.41%).

Table 8. LCI inventory for ammonia plant. Case 2 "Urea and UAN synthesis from natural gas with CO_2 capture".

CASE 2. Ammonia plant (Natural gas case with CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Ammonia liquid	tonne/day	2,000	2,000	2,000	2,000	Used as feedstock for Urea and Nitric Acid synthesis.	Basis of Design
Byproduct							
CO_2 to Urea Plant	tonne/day	2,510	2,510	2,510	2,510	Fed to the Urea Plant as feedstock for Urea Synthesis Reaction.	Calculation
Steam to Urea Plant	tonne/day	2,558	2,557	2,559	2,565	Fed to the Urea Plant as utility steam.	Calculation
Steam to Nitric Acid plant	tonne/day	9.2	9.2	9.2	9.2	Fed to the Nitric Acid Plant as utility steam.	Calculation
LP Steam to CCS Unit	tonne/day	1,123	1,123	1,123	1,123	Fed to CCS unit as utility steam.	Calculation
MP Steam to CCS Unit	tonne/day	3.2	3.2	3.2	3.2	Fed to CCS unit as utility steam.	Calculation
Water to BFW plant (Utilities)	m^3/day	2,629	2,630	2,628	2,622	Water recovered from the process and utilities condensates, and sent to the BFW plant	Calculation
Resources							
Air	tonne/day	2,349	2,349	2,349	2,349	Feedstock for ammonia production.	Calculation

CASE 2. Ammonia plant (Natural gas case with CO_2 capture)

	UM	Value (UK)	Value (Norway)	Value (US)	Value (Middle East)	Note	Source
Water (cooling water)	m^3/day	103,932	103,742	104,516	106,564	Sea Water (lake water in case of US) heated by 7/10°C by primary cooling circuit.	Calculation
Water (boiler feedwater)	m^3/day	7,800	7,800	7,800	7,800	BFW is used both for utility steam production and for process steam. Utility steam is used for multiple purposes: some is expanded in turbine drivers and is recovered, some is exported to Urea plant. Process steam is fed to the steam reformer, and most of it reacts with hydrocarbons, while the rest is partially recovered.	Calculation
Materials/fuels							
Natural gas (as feedstock)	Sm^3/day	1,211,128	1,211,128	1,211,128	1,211,128	Used as feedstock for SMR.	Calculation
Natural gas (as fuel)	Sm^3/day	476,455	476,455	476,455	476,455	Used as fuel for heating SMR.	Calculation
Catalyst:							
Zinc Oxide based catalyst	m^3/day	0.36	0.36	0.36	0.36	This value is the daily consumption (24 h without interruption). This catalyst is used in desulfurizer reactor, and it is generally substituted once every 6 months.	Literature
Nickel based catalyst for primary reformer	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature
Nickel based catalyst for autothermal reformer	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature

CASE 2. Ammonia plant (Natural gas case with CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Iron based catalyst promoted by Chromium/Copper oxides	m^3/day	0.05	0.05	0.05	0.05	This value is the daily consumption (24 h without interruption). This catalyst is used in HT shift reactor, and it is generally substituted once every 4 years.	Literature
Copper based catalyst	m^3/day	0.06	0.06	0.06	0.06	This value is the daily consumption (24 h without interruption). This catalyst is used in LT shift reactor, and it is generally substituted once every 4 years.	Literature
Nickel based catalyst for methanator reactor	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature
Magnetite based catalyst	m^3/day	0.09	0.09	0.09	0.09	This value is the daily consumption (24 h without interruption). This catalyst is used in ammonia synthesis reactor, and it is generally substituted once every 4 years.	Literature
Solvent (aMDEA)	tonne/day	-	-	-	-	Not available, depends on licensor	
Electricity/heat							
Electricity	kWh/day	472,537	469,105	473,682	490,845	Covers all the electric demand of the ammonia plant. Input from external.	Calculation
Emissions to air							
Heat	MJ/day	13,698,583	13,698,583	13,698,583	13,698,583	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Emissions to water							

CASE 2. Ammonia plant (Natural gas case with CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
NH_3 or NH_4 (as N)	kg/day	-	-	-	-	Negligible.	Literature
Waste to treatment							
Wastewater	m^3/day	100	100	100	100	Sent to wastewater treatment.	Calculation
Spent catalyst	tonne/day	-	-	-	-	Usually the spent catalyst is collected from the catalyst vendor. It applies to all the catalysts cited in the previous rows.	
Spent solvent	tonne/day	-	-	-	-	Recovered.	Calculation

Table 9. LCI inventory for CO_2 capture unit. Case 2 “Urea and UAN synthesis from natural gas with CO_2 capture”.

CASE 2. CO_2 Capture Unit							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
CO_2 to storage	tonne/day	976	976	976	976	Compressed CO_2 sent to storage	Calculation
Byproduct							
Water to BFW plant (Utilities)	m^3/day	1,973	1,973	1,973	1,973	Water recovered from the process and utilities condensates, and sent to the Demi Water plant	Calculation
Resources							
Water (cooling water)	m^3/day	20,109	20,109	20,109	20,109	Sea Water (lake water in case of US) heated by 7/10°C by primary cooling circuit.	Calculation
LP Steam	tonne/day	1,123	1,123	1,123	1,123	LP Steam fed to the CO2 stripper reboiler	Calculation
MP Steam	tonne/day	3.2	3.2	3.2	3.2	MP Steam fed to the solvent treatment unit	Calculation
Materials/fuels							
Solvent (proprietary)	tonne/day	-	-	-	-	Not available, depends on licensor	
Electricity/heat							
Electricity	kWh/day	101,815	101,557	102,844	105,933	Covers all the electric demand of the CCS plant. Input from external.	Calculation

CASE 2. CO_2 Capture Unit							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Emissions to air							
O_2	kg/day	126,937	126,937	126,937	126,937		Calculation
H_2O	kg/day	71,280	71,280	71,280	71,280		Calculation
NO_X	kg/day	< 559.3	< 559.3	< 559.3	< 559.3	Maximum value ensured by BAT, as stated in BoD.	Calculation
CO	kg/day	< 139.8	< 139.8	< 139.8	< 139.8	Maximum value ensured by BAT, as stated in BoD.	Calculation
CO_2, fossil	kg/day	114,411	114,411	114,411	114,411		Calculation
SO_X	kg/day	-	-	-	-	Negligible, since the feed gas contains only 5 ppm of sulphur, and it is further desulphurized.	Literature
Heat	MJ/day	3472627	3524381	3,458,631	3,290,410	Heat from: -Flue gases -CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 10. LCI inventory for urea synthesis plant. Case 2 “Urea and UAN synthesis from natural gas with CO_2 capture”.

CASE 2. Urea Synthesis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Liquid Urea to granulation	tonne/day	3167	3167	3167	3167	Urea to granulation plant.	calculation
Urea solution 77% to UAN plant.	tonne/day	235.6	235.6	235.6	235.6	Number indicates 77% Urea solution to UAN. (181.4 t/d of 100% Urea).	calculation
Byproduct							
Water to BFW plant (Utilities)	m^3/day	3,365	3,365	3,365	3,365	Water recovered from the process and utilities condensates, and sent to the BFW plant.	calculation
Steam to Urea granulation plant	tonne/day	63	63	63	63	LP Steam sent to Urea granulation plant	calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	Urea Plant only uses cooling water from a closed circuit.	literature
Steam	tonne/day	2,679	2,679	2,679	2,679	MP steam from Ammonia plant and Nitric Acid Plant.	calculation
Materials/fuels							
Ammonia liquid	tonne/day	1,898	1,898	1,898	1,898	Feedstock for Urea production.	calculation
CO_2	tonne/day	2,510	2,510	2,510	2,510	Feedstock for Urea production.	calculation
Electricity/heat							
Electricity	kWh/day	70,320	70,320	70,320	70,320	Electricity consumed in the synthesis plant.	calculation
Heat from natural gas	MJ/day	-	-	-	-	No heat from NG.	literature
Emissions to air							
Heat	MJ/day	11,170,628	11,170,628	11,170,628	11,170,628	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

CASE 2. Urea Synthesis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Waste to treatment							
Wastewater	m^3/day	201	201	201	201	Sent to wastewater treatment.	Calculation

Table 11. LCI inventory for urea granulation plant. Case 2 “Urea and UAN synthesis from natural gas with CO_2 capture”.

CASE 2. Urea Granulation plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Urea (granulate)	tonne/day	3,167	3,167	3,167	3,167	Urea Product.	Calculation
Byproduct							
Water to BFW (Utilities)	m^3/day	63	63	63	63	Steam condensate sent back to BFW plant	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	Urea Plant only uses cooling water from a closed circuit.	Literature
Steam	tonne/day	63	63	63	63	LP steam from Urea synthesis plant.	Calculation
Materials/fuels							
Formaldehyde	tonne/day	31.7	31.7	31.7	31.7	Granulation agent in Urea granulation plant.	literature
Electricity/heat							
Electricity	kWh/day	110,832	110,832	110,832	110,832	Electricity consumed in the granulation plant.	Calculation
Heat from natural gas	MJ/day	-	-	-	-	No heat from NG.	Literature
Emissions to air							

CASE 2. Urea Granulation plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Ammonia	kg/day	106	106	106	106	From Granulation tower. Maximum value ensured by BAT, as stated in BoD.	Calculation
Particulates	kg/day	211	211	211	211	From Granulation tower. Maximum value ensured by BAT, as stated in BoD.	Calculation
Heat	MJ/day	172,333	172,333	172,333	172,333	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 12. LCI inventory for nitric acid plant. Case 2 “Urea and UAN synthesis from natural gas with CO_2 capture”.

CASE 2. Nitric acid plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Nitric acid to ANS plant	tonne/day	303.8	303.8	303.8	303.8	Number indicates 60% NA solution. (182.3 t/d of 100% nitric acid). This stream is used as feedstock for ANS production.	Calculation
Nitric acid to UAN plant	tonne/day	4.4	4.4	4.4	4.4	Number indicates 60% NA solution. (2.6 t/d of 100% nitric acid). This stream is used as to neutralize slipstreams of ammonia in UAN.	Calculation
Byproduct							
Steam	tonne/day	120.2	121.3	119.3	113.3	MP steam to Urea plant.	Calculation
Water to BFW plant (Utilities)	m^3/day	74.0	72.9	74.8	80.9	Water from turbine condensate.	Calculation
Resources							

CASE 2. Nitric acid plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water (cooling water)	m^3/day	4,837.9	4,760.8	4,881.5	5,273.2	Sea Water (lake water in case of US) heated by 7/10°C by primary cooling circuit.	Calculation
Water (boiler feedwater)	m^3/day	184.9	184.9	184.9	184.9	Water used for steam production.	Calculation
Water (demineralized water)	m^3/day	61.0	61.0	61.0	61.0	Water used for process purpose (nitric oxides absorption).	Calculation
Steam	tonne/day	9.2	9.2	9.2	9.2	Utility steam from Ammonia plant.	Calculation
Materials/fuels							
Ammonia liquid	tonne/day	101.5	101.5	101.5	101.5	Feedstock for Nitric Acid production.	Calculation
Air	tonne/day	845.3	845.3	845.3	845.3	Feedstock for Nitric Acid production.	Calculation
Catalyst:							
Platinum/rhodium catalyst gauze	kg/day	0.16	0.16	0.16	0.16	This value is the daily consumption (24 h without interruption). It is generally substituted once every 70 days.	Literature
De_NOx catalyst	kg/day	-	-	-	-	Not available.	
Electricity/heat							
Electricity	kWh/day	1,849	1,849	1,849	1,849	Covers all the electric demand of the NA plant.	Calculation
Emissions to air							
Ammonia	kg/day	< 2.15	< 2.15	< 2.15	< 2.15	< 5 ppm. Maximum value ensured by BAT, as stated in BoD.	Literature
Nitrogen oxides	kg/day	< 0.76	< 0.76	< 0.76	< 0.76	< 30 ppm. Maximum value ensured by BAT, as stated in BoD.	Literature
N_2O	kg/day	37	37	37	37	Maximum value ensured by BAT, as stated in BoD.	Literature

CASE 2. Nitric acid plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Platinum	g/day	6.1	6.1	6.1	6.1	Platinum vaporized from the catalyst gauze, and not recovered.	Literature
Water	kg/day	4,543	4,543	4,543	4,543		Literature
Heat	MJ/day	787,000	787,000	787,000	787,000	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Waste to treatment							
Spent catalyst	kg/day	-	-	-	-	Catalyst is substituted every 70 days. The spent catalyst is usually collected by vendor. 70% of vaporized Pt is recovered (14.2 g/day), 30% is lost (6.1 g/day).	Literature

Table 13. LCI inventory for ammonium nitrate plant. Case 2 “Urea and UAN synthesis from natural gas with CO_2 capture”.

CASE 2. Ammonium nitrate plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Ammonium nitrate solution to UAN	tonne/day	249.8	249.8	249.8	249.8	Number indicates 92.5% AN solution. (231 t/d of 100% ammonium nitrate)	Calculation
Byproduct							
Water to Demi water plant (Utilities)	tonne/day	104.7	104.7	104.7	104.7	Water obtained from process, sent back to Demi Water plant	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	ANS Plant only uses cooling water from a closed circuit.	
Materials/fuels							
Ammonia liquid	tonne/day	49.2	49.2	49.2	49.2	Feedstock for ANS production	Calculation
Nitric acid	tonne/day	303.8	303.8	303.8	303.8	Feedstock for ANS production (in a 60% solution)	Calculation
Limestone	tonne/day	-	-	-	-	This chemical should be used only in case of upset of Urea /UAN plant to produce granulated AN	
Magnesium nitrate ($MgNO_3$)	tonne/day	-	-	-	-	This chemical should be used only in case of upset of Urea /UAN plant to produce granulated AN	
Electricity/heat							
Electricity	kWh/day	693.1	693.1	693.1	693.1	Covers all the electric demand of the ANS plant.	Calculation
Emissions to air							
Heat	MJ/day	245,633	245,633	245,633	245,633	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 14. LCI inventory for urea ammonium nitrate solution (UAN 32-0-0) plant. Case 2 "Urea and UAN synthesis from natural gas with CO_2 capture".

CASE 2. Urea ammonium nitrate solution (32-0-0) plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Urea ammonium nitrate solution (32-0-0)	tonne/day	520.9	520.9	520.9	520.9	UAN product	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	UAN Plant only uses cooling water from a closed circuit.	
Materials/fuels							
Urea 77% Solution	tonne/day	235.6	235.6	235.6	235.6	Feedstock for UAN	Calculation
Nitric acid 60% Solution	tonne/day	4.4	4.4	4.4	4.4	Feedstock for UAN	Calculation
Ammonium nitrate 92.5% solution	tonne/day	249.8	249.8	249.8	249.8	Feedstock for UAN	Calculation
Demineralized water	tonne/day	31.1	31.1	31.1	31.1	Feedstock for UAN	Calculation
Electricity/heat							
Electricity	kWh/day	182	182	182	182		Calculation
Emissions to air							
Heat	MJ/day	106,840	106,840	106,840	106,840	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 15. LCI inventory for utilities and balance of plant. Case 2 “Urea and UAN synthesis from natural gas with CO_2 capture”.

CASE 2. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
BFW to ammonia plant	m^3/day	7,800.0	7,800.0	7,800.0	7,800.0		Calculation
BFW to Nitric Acid plant	m^3/day	184.9	184.9	184.9	184.9		Calculation
Demi water to Nitric Acid plant	m^3/day	61.0	61.0	61.0	61.0		Calculation
Demi water to UAN plant	m^3/day	31.1	31.1	31.1	31.1		Calculation
Resources							
Water (cooling water)[8]	m^3/day	42,099	42,099	42,099	42,099	This is the sea water makeup to cooling tower (lake water for US) to cover the losses by evaporation/drift from the cooling tower (lost in the atmosphere).	Calculation
Water recovered from Ammonia Plant	m^3/day	2,629	2,630	2,628	2,622		Calculation
Water recovered from CCS plant	m^3/day	1,973	1,973	1,973	1,973		Calculation
Water recovered from Urea Plant	m^3/day	3,365	3,365	3,365	3,365		Calculation
Water recovered from Urea Granulation Plant	m^3/day	63	63	63	63		Calculation
Water recovered from Nitric Acid Plant	m^3/day	74	73	75	81		Calculation
Water recovered from Ammonium Nitrate Plant	m^3/day	105	105	105	105		Calculation

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[8] In order to allocate this water consumption to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (46.64%), CCS unit (10.86%), urea synthesis plant (38.03%), urea granulation plant (0.59%), nitric acid plant (2.68%), ammonium nitrate plant (0.84%), UAN plant (0.36%).

CASE 2. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Makeup water[9]	m^3/day	6,410	6,410	6,410	6,410	This stream is the makeup water for the demi water and BFW plant. - Normally it is obtained by demineralization (and a little treatment for BFW) of raw water. - In the Middle East case it comes from sea water which also needs to be desalinated. and hence it requires higher electric consumption.	Calculation
Electricity/heat							
Electricity[10]	kWh/day	189,093	189,093	189,093	227,550		Calculation
Emissions to air							

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[9] In order to allocate this water consumption to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia plant (56.08%), CCS unit (14.18%), urea synthesis plant (26.48%), urea granulation plant (0.46%), nitric acid plant (1.83%), ammonium nitrate plant (0.75%), UAN plant (0.22%).

[10] In order to allocate this electricity consumption to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant, since it constitutes the larger part of the utilities energy demand. The percentage attributed to each plant is the following: ammonia plant (46.64%), CCS unit (10.86%), urea synthesis plant (38.03%), urea granulation plant (0.59%), nitric acid plant (2.68%), ammonium nitrate plant (0.84%), UAN plant (0.36%).

CASE 2. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Water (cooling water)[11]	m³/day	42,099	42,099	42,099	42,099	These are the sea water losses from the cooling tower (lake water for US) (evaporation/drift from the cooling tower) (lost in the atmosphere).	Calculation
Emissions to water							
Water losses from BFW and Demi water plant[12]	m³/day	161.5	161.5	161.5	161.5	This is the water lost from the BFW and demi water plant because of leakage	Calculation
CW losses from CW loop[13]	m³/day	6,379	6,379	6,379	6,379	This is the Cooling Water lost from the CW closed loop because of leakage	Calculation

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[11] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (46.64%), CCS unit (10.86%), urea synthesis plant (38.03%), urea granulation plant (0.59%), nitric acid plant (2.68%), ammonium nitrate plant (0.84%), UAN plant (0.36%).

[12] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia plant (56.08%), CCS unit (14.18%), urea synthesis plant (26.48%), urea granulation plant (0.46%), nitric acid plant (1.83%), ammonium nitrate plant (0.75%), UAN plant (0.22%).

[13] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (46.64%), CCS unit (10.86%), urea synthesis plant (38.03%), urea granulation plant (0.59%), nitric acid plant (2.68%), ammonium nitrate plant (0.84%), UAN plant (0.36%).

Table 16. LCI inventory for ammonia plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Ammonia plant (Hybrid Natural gas/Electrolysis case with CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Ammonia liquid	tonne/day	2,000	2,000	2,000	2,000	Used as feedstock for Urea and Nitric Acid synthesis.	Basis of Design
Byproduct							
CO_2 to Urea Plant	tonne/day	1,888	1,888	1,888	1,888	Fed to the Urea Plant as feedstock for Urea Synthesis Reaction.	Calculation
Steam to Urea Plant	tonne/day	806	810	790	742	Fed to the Urea Plant as utility steam.	Calculation
Steam to Nitric Acid plant	tonne/day	9.2	9.2	9.2	9.2	Fed to the Nitric Acid Plant as utility steam.	Calculation
LP Steam to CCS Unit	tonne/day	669	669	669	669	Fed to CCS unit as utility steam.	Calculation
MP Steam to CCS Unit	tonne/day	1.9	1.9	1.9	1.9	Fed to CCS unit as utility steam.	Calculation
Water to BFW plant (Utilities)	m^3/day	3,581	3,578	3,597	3,645	Water recovered from the process and utilities condensates. and sent to the BFW plant	Calculation
Resources							
Air	tonne/day	2,377	2,377	2,377	2,377	Feedstock for ammonia production.	Calcuation
Water (cooling water)	m^3/day	103,932	103,742	104,516	106,564	Sea Water (lake water in case of US) heated by 7°C by primary cooling circuit.	Calculation
Water (boiler feedwater)	m^3/day	6,109	6,109	6,109	6,109	BFW is used both for utility steam production and for process steam. Utility steam is used for multiple purposes: some is expanded in turbine drivers and is recovered. some is exported to Urea plant. Process steam is fed to the steam reformer and most of it reacts with hydrocarbons. while the rest is partially recovered.	Calculation
Hydrogen from Electrolysis plant	tonne/day	107	107	107	107	Hydrogen obtained via Water electrolysis	Calculation

CASE 3. Ammonia plant (Hybrid Natural gas/Electrolysis case with CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Materials/fuels							
Natural gas (as feedstock)	Sm^3/day	916,951	916,951	916,951	916,951	Used as feedstock for SMR.	Calculation
Natural gas (as fuel)	Sm^3/day	281,305	281,305	281,305	281,305	Used as fuel for heating SMR.	Calculation
Catalyst:							
Zinc Oxide based catalyst	m^3/day	0.27	0.27	0.27	0.27	This value is the daily consumption (24 h without interruption). This catalyst is used in desulfurizer reactor and it is generally substituted once every 6 months.	Literature
Nickel based catalyst for primary reformer	m^3/day	0.02	0.02	0.02	0.02	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature
Nickel based catalyst for autothermal reformer	m^3/day	0.02	0.02	0.02	0.02	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature
Iron based catalyst promoted by Chromium/Copper oxides	m^3/day	0.03	0.03	0.03	0.03	This value is the daily consumption (24 h without interruption). This catalyst is used in HT shift reactor. and it is generally substituted once every 4 years.	Literature
Copper based catalyst	m^3/day	0.05	0.05	0.05	0.05	This value is the daily consumption (24 h without interruption). This catalyst is used in LT shift reactor. and it is generally substituted once every 4 years.	Literature
Nickel based catalyst for methanator reactor	m^3/day	0.02	0.02	0.02	0.02	This value is the daily consumption (24 h without interruption). It is generally substituted once every 4 years.	Literature

CASE 3. Ammonia plant (Hybrid Natural gas/Electrolysis case with CO_2 capture)							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Magnetite based catalyst	m^3/day	0.09	0.09	0.09	0.09	This value is the daily consumption (24 h without interruption). This catalyst is used in ammonia synthesis reactor and it is generally substituted once every 4 years.	Literature
Solvent (aMDEA)	tonne/day	-	-	-	-	Not available, depends on licensor	
Electricity/heat							
Electricity	kWh/day	452,055	448,581	453,213	470,580	Covers all the electric demand of the ammonia plant. Input from external.	Calculation
Emissions to air							
Heat	MJ/day	12,191,623	12,191,623	12,191,623	12,191,623	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Emissions to water							
NH_3 or NH_4 (as N)	kg/day	-	-	-	-	Negligible.	Literature
Waste to treatment							
Wastewater	m^3/day	70	70	70	70	Sent to wastewater treatment.	Calculation
Spent catalyst	tonne/day	-	-	-	-	Usually the spent catalyst is collected from the catalyst vendor. It applies to all the catalysts cited in the previous rows.	
Spent solvent	tonne/day	-	-	-	-	Recovered.	Calculation

Table 17. LCI inventory for CO_2 capture unit. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. CO_2 Capture Unit							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
CO_2 to Urea Plant	tonne/day	589	589	589	589	Compressed CO_2 sent to storage	Calculation
Byproduct							
Water to BFW plant (Utilities)	m^3/day	971	971	971	971	Water recovered from the process and utilities condensates and sent to the Demi Water plant	Calculation
Resources							
LP Steam	tonne/day	669	669	669	669	LP Steam fed to the CO_2 stripper reboiler	Calculation
MP Steam	tonne/day	1.9	1.9	1.9	1.9	MP Steam fed to the solvent treatment unit	Calculation
Materials/fuels							
Solvent (proprietary)	tonne/day	-	-	-	-	Not available. depends on licensor	
Electricity/heat							
Electricity	kWh/day	14,479	14,479	14,479	14,479	Covers all the electric demand of the CCS plant. Input from external.	calculation
Heat from natural gas	MJ/day	-	-	-	-	No heat from NG.	literature
Emissions to air							
O_2	kg/day	83,400	83,400	83,400	83,400		Calculation
H_2O	kg/day	227,073	227,073	227,073	227,073		Calculation
NO_X	kg/day	< 340.6	< 340.6	< 340.6	< 340.6	Maximum value ensured by BAT, as stated in BoD.	Calculation
CO	kg/day	< 85.2	< 85.2	< 85.2	< 85.2	Maximum value ensured by BAT, as stated in BoD.	Calculation
CO_2, fossil	kg/day	64,466	64,466	64,466	64,466		Calculation
H_2S	kg/day	-	-	-	-		

CASE 3. CO_2 Capture Unit							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
SO_X	kg/day	-	-	-	-	Negligible, since the feed gas contains only 5 ppm of sulphur, and it is further desulphurized.	literature
Heat	MJ/day	2,431,168.29	2,463,827.494	2,422,441.89	2,223,117.094	Heat from: -Flue gases -CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 18. LCI inventory for water electrolysis plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Water Electrolysis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Hydrogen to Ammonia Plant	tonne/day	107	107	107	107	Hydrogen sent to mix with syngas from NG to be used as feedstock for ammonia production	Calculation
Resources							
Demi Water	tonne/day	1,021	1,021	1,021	1,021	Water feedstock to electrolysis plant	Calculation
Materials/fuels							
Electrolyte (proprietary)	tonne/day	-	-	-	-	Not available, depends on licensor	
Electricity/heat							
Electricity	kWh/day	6,004,946	6,004,946	6,004,946	6,004,946	Covers all the electric demand of the Electrolysis plant. Input from external.	calculation
Emissions to air							

CASE 3. Water Electrolysis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
O_2	kg/day	453,707	453,707	453,707	453,707	Oxygen released to atmosphere	Calculation
Heat	MJ/day	2,212,030	2,212,030	2,212,030	2,212,030	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 19. LCI inventory for urea synthesis plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Urea Synthesis plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Liquid Urea to granulation	tonne/day	3,167	3,167	3,167	3,167	Urea to granulation plant.	Calculation
Urea solution 77% to UAN plant.	tonne/day	235.6	235.6	235.6	235.6	Number indicates 77% Urea solution to UAN. (181.4 t/d of 100% Urea).	Calculation
Byproduct							
Water to BFW plant (Utilities)	m^3/day	1,611	1,611	1,611	1,611	Water recovered from the process and utilities condensates, and sent to the BFW plant.	Calculation
Steam to Urea granulation plant	tonne/day	63	63	63	63	LP Steam sent to Urea granulation plant	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	Urea Plant only uses cooling water from a closed circuit.	Literature
Steam	tonne/day	925	925	925	925	MP steam from Ammonia plant and Nitric Acid Plant.	Calculation
Materials/fuels							

CASE 3. Urea Synthesis plant

	UM	Value (UK)	Value (Norway)	Value (US)	Value (Middle East)	Note	Source
Ammonia liquid	tonne/day	1,898	1,898	1,898	1,898	Feedstock for Urea production.	Calculation
CO_2	tonne/day	2,477	2,477	2,477	2,477	Feedstock for Urea production.	Calculation
Electricity/heat							
Electricity	kWh/day	439,250	439,250	439,250	439,250	Electricity consumed in the synthesis plant.	Calculation
Emissions to air							
Heat	MJ/day	11,170,628	11,170,628	11,170,628	11,170,628	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Waste to treatment							
Wastewater	m^3/day	201	201	201	201	Sent to wastewater treatment.	Calculation

Table 20. LCI inventory for urea granulation plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Urea Granulation plant

	UM	Value (UK)	Value (Norway)	Value (US)	Value (Middle East)	Note	Source
Product							
Urea (granulate)	tonne/day	3,167	3,167	3,167	3,167	Urea Product.	Calculation
Byproduct							
Water to BFW (Utilities)	m^3/day	63	63	63	63	Steam condensate sent back to BFW plant	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	Urea Plant only uses cooling water from a closed circuit.	Literature
Steam	tonne/day	63	63	63	63	LP steam from Urea synthesis plant.	Calculation

CASE 3. Urea Granulation plant

	UM	Value (UK)	Value (Norway)	Value (US)	Value (Middle East)	Note	Source
Materials/fuels							
Formaldeyde	tonne/day	31.7	31.7	31.7	31.7	Granulation agent in Urea granulation plant.	Literature
Electricity/heat							
Electricity	kWh/day	110,832	110,832	110,832	110,832	Electricity consumed in the granulation plant.	Calculation
Emissions to air							
Ammonia	kg/day	106	106	106	106	From Granulation tower. Maximum value ensured by BAT, as stated in BoD.	Calculation
Particulates	kg/day	211	211	211	211	From Granulation tower. Maximum value ensured by BAT, as stated in BoD.	Calculation
Heat	MJ/day	172,333	172,333	172,333	172,333	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 21. LCI inventory for nitric acid plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Nitric acid plant

	UM	Value (UK)	Value (Norway)	Value (US)	Value (Middle East)	Note	Source
Product							
Nitric acid to ANS plant	tonne/day	303.8	303.8	303.8	303.8	Number indicates 60% NA solution. (182.3 t/d of 100% nitric acid). This stream is used as feedstock for ANS production.	Calculation
Nitric acid to UAN plant	tonne/day	4.4	4.4	4.4	4.4	Number indicates 60% NA solution. (2.6 t/d of 100% nitric acid). This stream is used as fto neutralize slipstreams of ammonia in UAN.	Calculation
Byproduct							

CASE 3. Nitric acid plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Steam	tonne/day	120.2	121.3	119.3	113.3	MP steam to Urea plant.	Calculation
Water to BFW plant (Utilities)	m^3/day	74.0	72.9	74.8	80.9	Water from turbine condensate.	Calculation
Resources							
Water (cooling water)	m^3/day	4,837.9	4,760.8	4,881.5	5,273.2	Sea Water (lake water in case of US) heated by 7/10°C by primary cooling circuit.	Calculation
Water (boiler feedwater)	m^3/day	184.9	184.9	184.9	184.9	Water used for steam production.	Calculation
Water (demineralized water)	m^3/day	61.0	61.0	61.0	61.0	Water used for process purpose (nitric oxides absorption).	Calculation
Steam	tonne/day	9.2	9.2	9.2	9.2	Utility steam from Ammonia plant.	Calculation
Materials/fuels							
Ammonia liquid	tonne/day	101.5	101.5	101.5	101.5	Feedstock for Nitric Acid production.	Calculation
Air	tonne/day	845.3	845.3	845.3	845.3	Feedstock for Nitric Acid production.	Calculation
Catalyst:							
Platinum/rhodium catalyst gauze	kg/day	0.16	0.16	0.16	0.16	This value is the mass of catalyst employed in the plant. This catalyst is used in nitric acid synthesis reactor, and it is generally substituted once every 70 days.	Literature
De_NOx catalyst	kg/day	-	-	-	-	Not available.	
Electricity/heat							
Electricity	kWh/day	1,849	1,849	1,849	1,849	Covers all the electric demand of the NA plant.	Calculation
Emissions to air							
Ammonia	kg/day	< 2.15	< 2.15	< 2.15	< 2.15	< 5 ppm. Maximum value ensured by BAT. as stated in BoD.	Literature

CASE 3. Nitric acid plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Nitrogen oxides	kg/day	< 0.76	< 0.76	< 0.76	< 0.76	< 30 ppm. Maximum value ensured by BAT. as stated in BoD.	Literature
N_2O	kg/day	37	37	37	37	Maximum value ensured by BAT. as stated in BoD.	Literature
Platinum	g/day	6.1	6.1	6.1	6.1	Platinum vaporized from the catalyst gauze. and not recovered.	Literature
Water	kg/day	4,543	4,543	4,543	4,543		Literature
Heat	MJ/day	787,000	787,000	787,000	787,000	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation
Waste to treatment							
Spent catalyst	kg/day	-	-	-	-	Catalyst is substituted every 70 days. The spent catalyst is usually collected by vendor. 70% of vaporized Pt is recovered (14.2 g/day). 30% is lost (6.1 g/day).	Literature

Table 22. LCI inventory for ammonium nitrate plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Ammonium nitrate plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Ammonium nitrate solution to UAN	tonne/day	249.8	249.8	249.8	249.8	Number indicates 92.5% AN solution. (231 t/d of 100% ammonium nitrate)	Calculation
Byproduct							
Water to Demi water plant (Utilities)	tonne/day	104.7	104.7	104.7	104.7	Water obtained from process, sent back to Demi Water plant	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	ANS Plant only uses cooling water from a closed circuit.	
Materials/fuels							
Ammonia liquid	tonne/day	49.2	49.2	49.2	49.2	Feedstock for ANS production	Calculation
Nitric acid	tonne/day	303.8	303.8	303.8	303.8	Feedstock for ANS production (in a 60% solution)	Calculation
Limestone	ton/day	-	-	-	-	This chemical should be used only in case of upset of Urea /UAN plant to produce granulated AN	
Magnesium nitrate ($MgNO_3$)	tonne/day	-	-	-	-	This chemical should be used only in case of upset of Urea /UAN plant to produce granulated AN	
Electricity/heat							
Electricity	kWh/day	693.1	693.1	693.1	693.1	Covers all the electric demand of the ANS plant.	Calculation
Emissions to air							
Heat	MJ/day	245,633	245,633	245,633	245,633	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 23. LCI inventory for urea ammonium nitrate solution (UAN 32-0-0). Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Urea ammonium nitrate solution (32-0-0) plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							
Urea ammonium nitrate solution (32-0-0)	tonne/day	520.9	520.9	520.9	520.9	UAN product	Calculation
Resources							
Water (cooling water)	m^3/day	-	-	-	-	UAN Plant only uses cooling water from a closed circuit.	
Materials/fuels							
Urea 77% Solution	tonne/day	235.6	235.6	235.6	235.6	Feedstock for UAN	Calculation
Nitric acid 60% Solution	tonne/day	4.4	4.4	4.4	4.4	Feedstock for UAN	Calculation
Ammonium nitrate 92.5% solution	tonne/day	249.8	249.8	249.8	249.8	Feedstock for UAN	Calculation
Demineralized water	tonne/day	31.1	31.1	31.1	31.1	Feedstock for UAN	Calculation
Electricity/heat							
Electricity	kWh/day	182	182	182	182		Calculation
Emissions to air							
Heat	MJ/day	106,840	106,840	106,840	106,840	Heat from CW (mainly disposed of as latent heat in cooling tower)	Calculation

Table 24. LCI inventory for utilities and balance of plant. Case 3 “Urea and UAN synthesis from hybrid natural gas/water electrolysis, with CO_2 capture”.

CASE 3. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Product							

CASE 3. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
BFW to ammonia plant	m^3/day	6,109.0	6,109.0	6,109.0	6,109.0		Calculation
Demi water to Electrolysis plant	m^3/day	1,020.8	1,020.8	1,020.8	1,020.8		Calculation
BFW to Nitric Acid plant	m^3/day	184.9	184.9	184.9	184.9		Calculation
Demi water to Nitric Acid plant	m^3/day	61.0	61.0	61.0	61.0		Calculation
Demi water to UAN plant	m^3/day	31.1	31.1	31.1	31.1		Calculation
Resources							
Water (cooling water)[14]	m^3/day	41,224	41,224	41,224	41,224	This is the sea water makeup to cooling tower (lake water for US) to cover the losses by evaporation/drift from the cooling tower (lost in the atmosphere).	Calculation
Water recovered from Ammonia Plant	m^3/day	3,581	3,578	3,597	3,645		Calculation
Water recovered from CCS plant	m^3/day	971	971	971	971		Calculation
Water recovered from Urea Plant	m^3/day	1,611	1,611	1,611	1,611		Calculation
Water recovered from Urea Granulation Plant	m^3/day	63	63	63	63		Calculation
Water recovered from Nitric Acid Plant	m^3/day	74	73	75	81		Calculation
Water recovered from Ammonium Nitrate Plant	m^3/day	105	105	105	105		Calculation

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[14] In order to allocate this water consumption to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (42.39%), CCS unit (6.52%), electrolysis plant (7.69%), urea synthesis plant (38.84%), urea granulation plant (0.60%), nitric acid plant (2.74%), ammonium nitrate plant (0.85%), UAN plant (0.37%).

CASE 3. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Makeup water[15]	m^3/day	7,396	7,396	7,396	7,396	This stream is the makeup water for the demi water and BFW plant. - Normally it is obtained by demineralization (and a little treatment for BFW) of raw water. - In the Middle East case it comes from sea water. which also needs to be desalinated. and hence it requires higher electric consumption.	Calculation
Electricity/heat							
Electricity[16]	kWh/day	186,546	186,546	186,546	230,921		Calculation

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[15] In order to allocate this water consumption to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia plant (58.27%), CCS unit (9.26%), electrolysis plant (9.74%), urea synthesis plant (18.40%), urea granulation plant (0.60%), nitric acid plant (2.43%), ammonium nitrate plant (1.00%), UAN plant (0.30%).

[16] In order to allocate this electricity consumption to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant, since it constitutes the larger part of the utilities energy demand. The percentage attributed to each plant is the following: ammonia plant (42.39%), CCS unit (6.52%), electrolysis plant (7.69), urea synthesis plant (38.84%), urea granulation plant (0.60%), nitric acid plant (2.74%), ammonium nitrate plant (0.85%), UAN plant (0.37%).

CASE 3. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
Emissions to air							
Water (cooling water)[17]	m^3/day	41,224	41,224	41,224	41,224	These are the sea water losses from the cooling tower (lake water for US) (evaporation/drift from the cooling tower) (lost in the atmosphere).	Calculation
Emissions to water							
Water losses from BFW and Demi water plant[18]	m^3/day	148.1	148.1	148.1	148.1	This is the water lost from the BFW and demi water plant because of leakage	Calculation

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[17] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (42.39%), CCS unit (6.52%), electrolysis plant (7.69%), urea synthesis plant (38.84%), urea granulation plant (0.60%), nitric acid plant (2.74%), ammonium nitrate plant (0.85%), UAN plant (0.37%).

[18] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the BFW and demi water circulating in each process plant. The percentage attributed to each plant is the following: ammonia plant (58.27%), CCS unit (9.26%), electrolysis plant (9.74%), urea synthesis plant (18.40%), urea granulation plant (0.60%), nitric acid plant (2.43%), ammonium nitrate plant (1.00%), UAN plant (0.30%).

CASE 3. Utilities and Balance of Plant							
	UM	**Value (UK)**	**Value (Norway)**	**Value (US)**	**Value (Middle East)**	**Note**	**Source**
CW losses from CW loop[19]	m^3/day	6,246	6,246	6,246	6,246	This is the Cooling Water lost from the CW closed loop because of leakage	Calculation

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[19] In order to allocate this water loss to each process plant, and hence to each product, we can use as a basis the water circulating in the cooling water closed loop of each process plant. The percentage attributed to each plant is the following: ammonia plant (42.39%), CCS unit (6.52%), electrolysis plant (7.69%), urea synthesis plant (38.84%), urea granulation plant (0.60%), nitric acid plant (2.74%), ammonium nitrate plant (0.85%), UAN plant (0.37%).

2. Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) aims to evaluate how significant are the potential environmental impacts related to the environmental loads quantified in the inventory analysis. Basically, the purpose of LCIA is to turn the inventory results into easier to understand environmental information, by means of converting the former into a reduced number of impact category indicators (such as the ones for global warming, acidification, ozone layer depletion or ecotoxicity). This process is carried out through successive steps, which are briefly described below. Classification and characterization are compulsory in LCA according to the ISO standards, whereas normalization and weighting are optional:

- **Classification**: this simply means sorting the inventory flows or substances according to the impact categories they contribute to. For example, CO_2 and CH_4 emissions are classified into "Climate Change" category.

- **Characterization**: this step consists of quantifying the contribution of the substances classified in each impact category, expressed in a common unit. This is done by using “characterization factors”; factors that show the relative contribution of one singular emission at a given impact category using a reference unit. Climate Change, for instance, is calculated in kg of CO_2 equivalent. Such characterization factors are based on scientific models of cause-effect chains in the natural systems. ISO standards (14040 and 14044) do not specify any particular set of characterization factors to be used, thus, different existing approaches developed by different research centres can be employed. At this point, the so-called "environmental profile", consisting of a set of impact categories expressed in their relative units, is obtained.

- **Normalization**: this step consists of dividing the characterized results by the real or the expected total amount of pollutants emitted in a geographical area at a given moment in time (for instance, the total emissions or resource use for a given area that may be global, regional or local). This gives the “relative importance” of the environmental effects caused by the system under study in a given area;

- **Weighting**: this step consists of converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices;

- **Grouping**: this step consists of sorting (e.g. by characteristics such as inputs and outputs or global regional and local spatial scales) and possibly ranking (e.g. high, medium and low priority) the impact categories;

- **Data quality analysis**: this step consists of a better understanding the reliability of the collection of indicator results using uncertainty analysis, sensitivity analysis etc.

The environmental impact assessment of the investigated nitrogen fertilizer (Urea and UAN 32.0.0 solution) production was modelled by means of LCA professional software Simapro 9 (Pre Consultants), using one of the most recent and up-to-date LCA method, the ILCD method version 1.11 (updated October 2019). The ILCD 2011 Midpoint impact assessment method was released by the European Commission, Joint Research Centre in 2012. The Method supports the correct use of the characterisation factors (to quantify the contribution of the different flows to and from a process to each impact category) for impact assessment as recommended in the ILCD guidance document "Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors (EC-JRC, 2012)[20]. The ILCD method also provides normalization factors (to allow a comparison across indicators) and weighting factors.

The ILCD method was chosen considering that it includes both upstream categories (i.e. referred to depletion of natural resources, such as fossil, metal and water depletion categories) and downstream categories (i.e. referred to impacts generated on natural matrices, such as terrestrial, marine or freshwater acidification).

The default 16 impact categories as listed in the ILCD handbook ‘Recommendations for LCIA in the European context’ (JRC-IES, 2012) are LCIA indicators calculated based on the ILCD method at midpoint level are listed and defined in table 25.

Table 25. Impact categories included in ILCD method.

Impact Categories	Indicator	Description
Climate Change (GWP 100)	kg CO_2 eq	Capacity of a greenhouse gas to influence radiative forcing. It relates to the capacity to influence changes in the global, average surface-air temperature and subsequent change in various climate parameters and their effects, such as storm frequency and intensity, rainfall intensity and frequency of flooding, etc.
Ozone Depletion	kg CFC-11 eq	Ozone Depletion accounts for the degradation of stratospheric ozone due to emissions of ozone depleting substances, for example long-lived chlorine and bromine-containing gases (e.g. CFCs, HCFCs, Halons).
Human Toxicity - cancer effects	CTUh	Human Toxicity –cancer - accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin inso far as they are related to cancer.

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[20] European Commission, Joint Research Centre, Institute for Environment and Sustainability, 2012. Characterization factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information. First edition. February 2012. EUR 25167. Luxembourg. Publications Office of the European Union.

Impact Categories	Indicator	Description
Human Toxicity – non- cancer effects	CTUh	Human Toxicity- non cancer – accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin inso far as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.
Particulate Matter/Respiratory Inorganics	kg PM2.5 eq	Particulate Matter/Respiratory Inorganics accounts for the adverse health effects on human health caused by emissions of Particulate Matter (PM) and its precursors (NOx , SOx , NH3)
Ionising Radiation, Human Health (HH)	kBq U235 eq	Ionising Radiation, human health accounts for the adverse health effects on human health caused by radioactive releases.
Ionising Radiation, Ecosystem (E)	CTU e	Ionising Radiation, ecosystem accounts for the adverse health effects on ecosystem caused by radioactive releases.
Photochemical Ozone Formation	kg NMVOC eq	Photochemical Ozone Formation accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of Volatile Organic Compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manmade materials through reaction with organic materials.
Acidification	molc H+ eq	Acidification addresses impacts due to acidifying substances in the environment. Emissions of NOx , NH3 and SOx lead to releases of hydrogen ions (H+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lakes acidification.
Terrestrial eutrophication	mol N eq	Nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of emission of substances into a common measure expressed as the oxygen required for the degradation of dead biomass.
Freshwater eutrophication	kg P eq	Nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of emission of substances into a common measure expressed as the oxygen required for the degradation of dead biomass.

Impact Categories	Indicator	Description
Marine eutrophication	kg N eq	Nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of emission of substances into a common measure expressed as the oxygen required for the degradation of dead biomass.
Freshwater ecotoxicity	kg P eq	Ecotoxicity addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.
Land use	kg C deficit	Land use relates to use (occupation) and conversion (transformation) of land area by activities such as agriculture, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in quality multiplied by the area).
Water resource depletion[21]	m^3 water eq	Resource Depletion addresses use of natural resources, either renewable or non-renewable, biotic or abiotic.
Mineral, fossil & renewable resource depletion	kg Sb eq	Resource Depletion addresses use of natural resources, either renewable or non-renewable, biotic or abiotic.

In this study, normalization and weighting phases were performed using normalization and weighting factors already implemented in the ILCD v.1.11 Method.

The normalization factors are based on "Normalization method and data for Environmental Footprints”[22]. The weighting factors are based on "European Commission, 2014, Environmental Footprint Pilot Guidance document, - Guidance for the implementation of the EU Product Environmental Footprint (PEF) during the Environmental Footprint (EF) pilot phase, v. 4.0, May 2014" (all impact categories shall receive the same weight in the baseline approach).

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[21] Water source (sea, lake, river or underground) does not have an impact on the results. For assessing water depletion, characterization factors based on countries’ water scarcity were implemented in ILCD Method, based on the Ecological Scarcity Method (Frischknecht et al 2008).

[22] Benini L., Mancini L., Sala S., Manfredi S., Schau E. M., Pant R., 2014. Normalisation method and data for Environmental Footprints. European Commission, Joint Research Center, Institute for Environment and Sustainability, Publications Office of the European Union, Luxemburg, ISBN: 978-92-79-40847-2

The three toxicity-related impact categories are temporarily excluded from the procedure to identify the most relevant impact categories as currently they are not seen as sufficiently robust to be included in external communications or in a weighted result. This decision will be reconsidered at the end of the PEF transition phase, after the finalisation of the ongoing work done in collaboration between the Commission and ECHA agency in Helsinki on developing new characterization factors based with REACH data[23].

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[23] European Commission, 2017. PEFCR Guidance document, - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3.

3. Results interpretation

Interpretation of the LCA is discussed in this section. Considering the assumptions of the present LCA study, the results obtained for the selected system boundaries referred to **one metric tonne of Urea and UAN 32.0.0.** solution produced (functional unit) are presented below. Since the CO_2 emissions, natural gas (NG), electricity and water sources and hydrogen production technology (only for electrolysis case, i.e. case 3), are the only changes among three investigated cases, the difference in results comes mainly from these parameters.

3.1. Environmental performance of Urea and UAN solution synthesis: the United Kingdom case study

Tables 26 and 27 summarize the characterized impacts of 1 tonne of Urea and 1 tonne of UAN 32.0.0 solution (functional unit-FU) solution production in UK by three investigated technologies.

Table 26. Characterized impacts calculated for urea synthesis in each case (UK case study).

Impact category	Unit/FU	Case 1. Urea synthesis, NG w/o CO_2 capt (UK case)	Case 2. Urea synthesis, NG with CO_2 capt (UK case)	Case 3. Urea synthesis, hybrid NG/ water electrolysis with CO_2 capt (UK case)
Climate change	kg CO_2 eq	472.856	213.992	814.266
Ozone depletion	kg CFC-11 eq	9.33E-05	9.50E-05	1.57E-04
Human toxicity, non-cancer effects	CTUh	2.32E-05	2.48E-05	9.37E-05
Human toxicity, cancer effects	CTUh	1.58E-06	1.65E-06	4.40E-06
Particulate matter	kg PM2.5 eq	0.044	0.047	0.177
Ionizing radiation HH	kBq U235 eq	68.274	74.038	329.871
Ionizing radiation E (interim)	CTUe	4.94E-04	5.37E-04	2.43E-03
Photochemical ozone formation	kg NMVOC eq	0.691	0.702	1.855
Acidification	molc H+ eq	0.908	0.945	3.086
Terrestrial eutrophication	molc N eq	2.928	2.968	7.672

Impact category	Unit/FU	Case 1. Urea synthesis, NG w/o CO_2 capt (UK case)	Case 2. Urea synthesis, NG with CO_2 capt (UK case)	Case 3. Urea synthesis, hybrid NG/ water electrolysis with CO_2 capt (UK case)
Freshwater eutrophication	kg P eq	0.004	0.004	0.023
Marine eutrophication	kg N eq	0.224	0.226	0.621
Freshwater ecotoxicity	CTUe	51.416	54.145	173.681
Land use	kg C deficit	231.044	248.036	999.604
Water resource depletion	m^3 water eq	3.007	3.502	3.174
Mineral, fossil & ren resource depletion	kg Sb eq	0.004	0.004	0.007

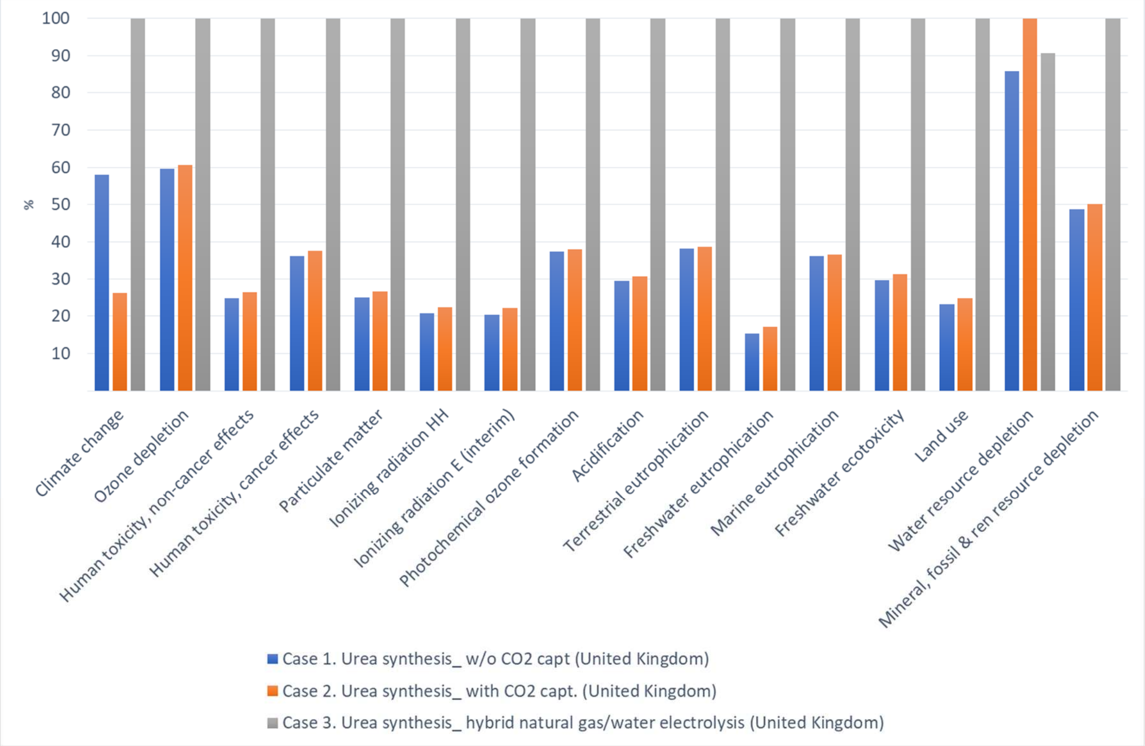

Figure 1. Characterized impacts calculated for urea synthesis in each case (United Kingdom case study).

As regards the urea granulate production in UK, the results in table 26 show that Case 2 has the lowest impact on climate change (releasing 214 kg CO_2 eq/tonne urea) with 55% lower than the benchmark case, i.e. Case 1 (473 kg CO_2 eq/tonne urea). The highest value is obtained in Case 3 (814 kg CO_2 eq/tonne urea) with about 42% increase over Case 1 and 74% over Case 2. For all cases, the liquid urea production process (synthetized from ammonia precursor) has the highest contribution to the climate change indicator, with an average value of 94% (data not shown), followed by electricity used for granulation process. For Case 1, ammonia production process-related emissions and natural gas (as feedstock) supply chain are the major contributing sources. For Case 2, natural gas (as feedstock) and CO_2 capture unit are significant contributor, whereas CO_2 emissions generated during ammonia synthesis are significantly reduced compared to the Case 1, i.e. benchmark (in Case 2, CO_2 is captured both syngas and SMR flue gases and exported from the plant as a product). The major contributor in Case 3 is the hydrogen supply chain, more specifically the electricity production necessary for electrolysis.

Even though the climate change for Case 2 has the lowest values amongst the investigated cases, the rest of the environmental impact categories do not follow the same trend. As it is possible to observe in figure 1, Case 2 performs slightly worst (up to 14% increase for water resources depletion due to a higher sea/lake water consumption used to accomplish the inter-refrigeration cooling duty of CO_2 compressors) if compared with Case 1. This can be explained by the fact that in the Case 2 the electrical consumption is higher than Case 1 (reference case) due to the power absorbed by the CO_2 capture and compression plant. Regarding the Case 3 (i.e. urea synthesis from ammonia produced by hybrid natural gas/water electrolysis route), the trend is generally increasing with over 40% in almost all environmental impacts indicators due to the majority of electrical power absorbed by the electrolysis plant. Only exception is observed for water resource depletion, whereas the impact is reduced (up to 10%) with respect to Case 2 and increased (up to 5%) compared to Case 1. In Case 3 the sea/lake water consumption is higher than the Case 1 because of the higher cooling duty in the cooling tower.

Table 27. Characterized impacts calculated for UAN synthesis in each case (UK case study).

Impact category	Unit/FU	Case 1. UAN synthesis, NG w/o CO_2 capt (UK case)	Case 2. UAN synthesis, NG with CO_2 capt (UK case)	Case 3. UAN synthesis, hybrid NG/ water electrolysis with CO_2 capt (UK case)
Climate change	kg CO_2 eq	457.137	213.686	801.624
Ozone depletion	kg CFC-11 eq	8.59E-05	8.95E-05	1.48E-04
Human toxicity, non-cancer effects	CTUh	2.08E-05	2.27E-05	9.16E-05
Human toxicity, cancer effects	CTUh	1.42E-06	1.51E-06	4.39E-06
Particulate matter	kg PM2.5 eq	0.046	0.049	0.216
Ionizing radiation HH	kBq U235 eq	59.795	66.588	310.027

Impact category	Unit/FU	Case 1. UAN synthesis, NG w/o CO_2 capt (UK case)	Case 2. UAN synthesis, NG with CO_2 capt (UK case)	Case 3. UAN synthesis, hybrid NG/ water electrolysis with CO_2 capt (UK case)
Ionizing radiation E (interim)	CTUe	4.32E-04	4.82E-04	2.28E-03
Photochemical ozone formation	kg NMVOC eq	0.697	0.720	2.170
Acidification	molc H+ eq	0.948	0.998	4.015
Terrestrial eutrophication	molc N eq	2.635	2.720	8.758
Freshwater eutrophication	kg P eq	0.003	0.004	0.024
Marine eutrophication	kg N eq	0.222	0.229	0.708
Freshwater ecotoxicity	CTUe	43.178	46.644	175.848
Land use	kg C deficit	257.871	278.215	1263.552
Water resource depletion	m^3 water eq	3.650	4.184	4.093
Mineral, fossil & ren resource depletion	kg Sb eq	0.004	0.004	0.011

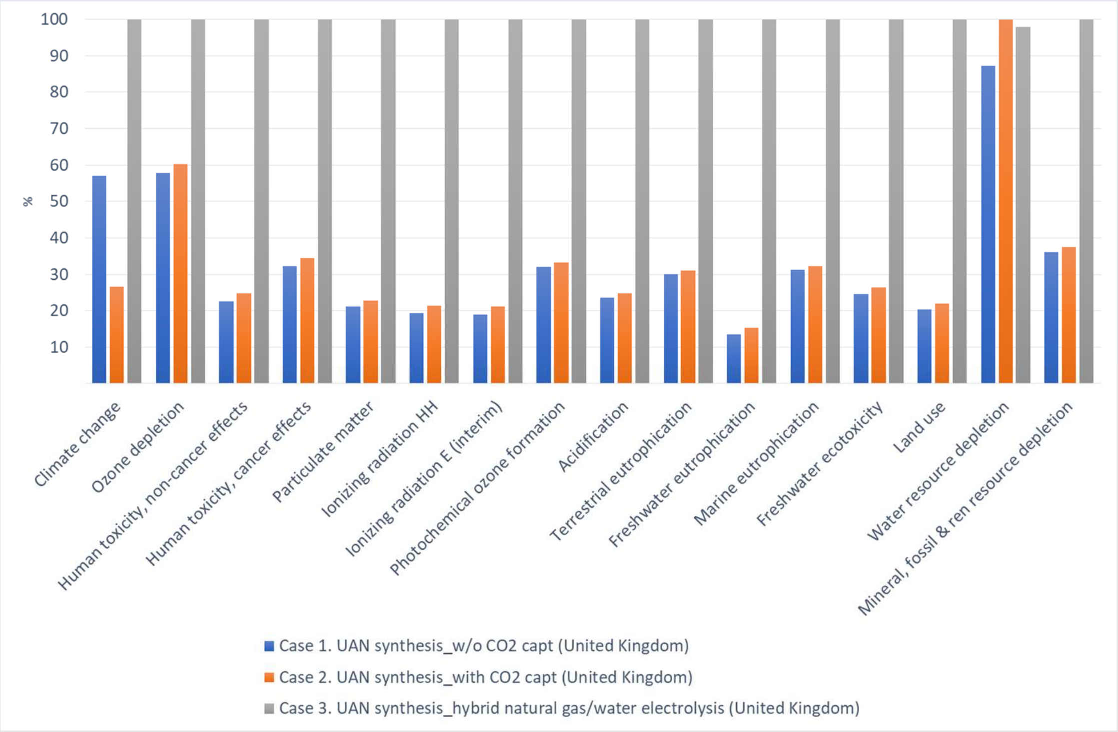

Figure 2. Characterized impacts calculated for UAN production in each case (United Kingdom case study).

Similar environmental performance is obtained for UAN solution production. For all cases, the ammonium nitrate solution (ANS) synthesis process has the highest contribution to all environmental impact categories, followed by urea solution 77% production process. Climate change indicator registers the lowest values for the Case 2 (214 kg CO_2 eq/tonne UAN), followed by Case 1 (457 kg CO2 eq/tonne UAN) and Case 3 (801 kg CO_2 eq/tonne UAN). As already observed for urea production, the results show a different trend on the rest of environmental indicators. Case 2 perform slightly worst if compared with Case 1, due to a higher power consumption related to CO_2 capture and storage section that occurs during ammonia synthesis process. Water resource depletion gives the highest value for Case 2 with 13% above Case 1 and 2% compared to Case 3. Case 3 has the worst environmental performance in almost all environmental indicators due to the highest specific energy consumption attributable to the electrolyser for hydrogen production (the contribution overcomes 50% in almost all indicators, except for water resource depletion). Natural gas supply chain contributes to environmental impacts for less than 30% while CO_2 capture section and electricity for ammonia synthesis contribute only at a minor extent (less than 6%).

3.2. Environmental performance of Urea and UAN solution synthesis: the Norway case study

Tables 28 and 29 summarize the characterized impacts of 1 tonne of Urea and 1 tonne of UAN 32.0.0 solution (functional unit-FU) solution production in Norway by three investigated technologies.

Table 28. Characterized impacts calculated for urea synthesis in each case (Norway case study).

Impact category	**Unit/FU**	**Case 1. Urea synthesis, NG w/o CO_2 capt (Norway case)**	**Case 2. Urea synthesis, NG with CO_2 capt (Norway case)**	**Case 3. Urea synthesis, hybrid NG/ water electrolysis with CO_2 capt (Norway case)**
Climate change	kg CO_2 eq	383.221	111.045	107.770
Ozone depletion	kg CFC-11 eq	6.17E-05	6.16E-05	4.74E-05
Human toxicity, non-cancer effects	CTUh	1.36E-05	1.37E-05	1.49E-05
Human toxicity, cancer effects	CTUh	1.24E-06	1.26E-06	1.89E-06
Particulate matter	kg PM2.5 eq	0.0259	0.0260	0.035
Ionizing radiation HH	kBq U235 eq	2.028	2.231	11.373
Ionizing radiation E (interim)	CTUe	1.51E-05	1.66E-05	8.45E-05
Photochemical ozone formation	kg NMVOC eq	0.540	0.523	0.438
Acidification	molc H+ eq	0.589	0.578	0.550
Terrestrial eutrophication	molc N eq	2.327	2.257	1.982
Freshwater eutrophication	kg P eq	0.001	0.001	0.002
Marine eutrophication	kg N eq	0.173	0.167	0.139
Freshwater ecotoxicity	CTUe	33.758	34.081	44.827
Land use	kg C deficit	55.214	54.986	37.074
Water resource depletion	m^3 water eq	0.026	0.034	0.233

Impact category	Unit/FU	Case 1. Urea synthesis, NG w/o CO_2 capt (Norway case)	Case 2. Urea synthesis, NG with CO_2 capt (Norway case)	Case 3. Urea synthesis, hybrid NG/ water electrolysis with CO_2 capt (Norway case)
Mineral, fossil & ren resource depletion	kg Sb eq	0.00256	0.00257	0.00240

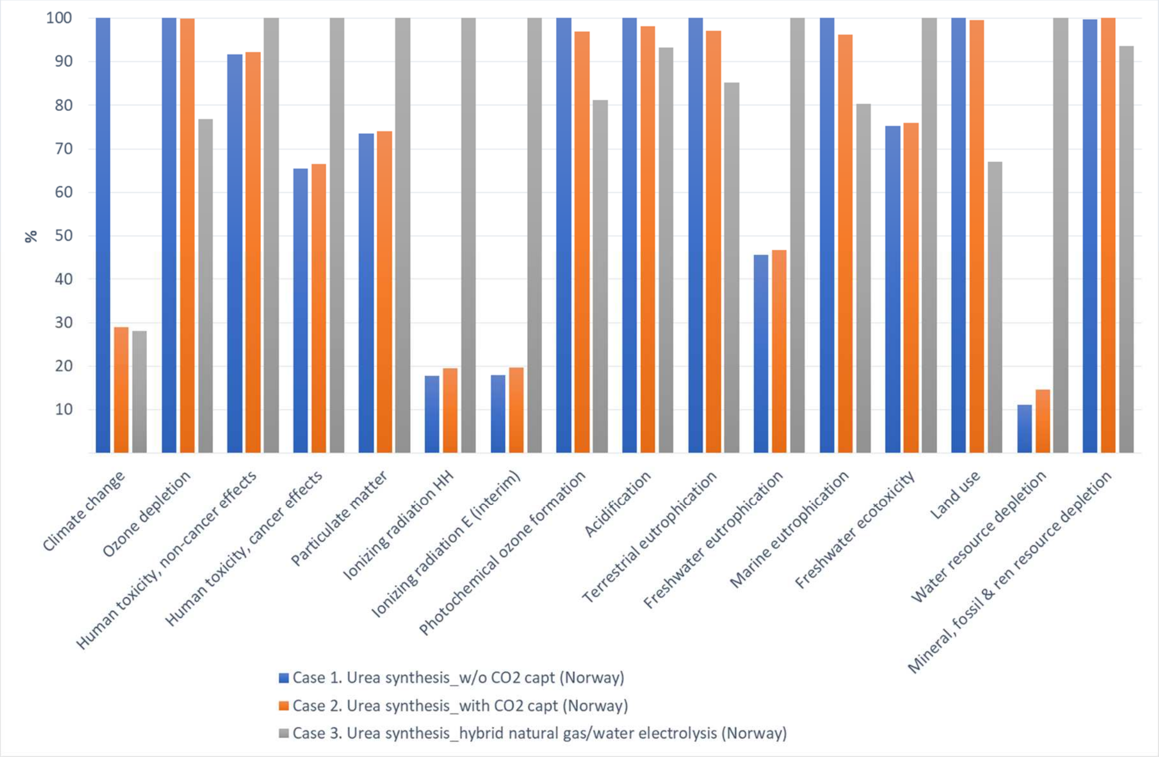

Figure 3. Characterized impacts calculated for urea synthesis in each case (Norway case study).

With regard to the urea granulate production in Norway, the results in table 28 show that Case 3 has the lowest impact on climate change (108 kg CO_2 eq/tonne urea) with 72% lower than the Case 1 (383 kg CO_2 eq/tonne urea) and 3% lower than Case 2 (111 kg CO_2 eq/tonne urea). For all cases, the liquid urea production process (synthetized from ammonia precursor) has the highest contribution to the climate change indicator, with an average value of 96% (data not shown), followed by electricity (3%) and formaldehyde chemical (1%) used in granulation process. Specifically, about Case 1, ammonia production process-related emissions and natural gas (as feedstock) supply chain resulted to be responsible for the main environmental loads. For Case 2, natural gas (as feedstock) and CO_2 capture unit are significant contributors, whereas emissions generated during ammonia synthesis are significantly reduced compared to the benchmark (in Case 2, CO_2 is captured both syngas and SMR flue gases and exported from the plant as a product). The major responsible in Case 3 are natural gas (as feedstock) and hydrogen supply chain, more specifically the electricity production necessary for electrolysis.

As regards the remaining impact categories, Case 1 (reference case) reports the highest values on ozone depletion, photochemical ozone formation, acidification, terrestrial and marine eutrophication and land use. Case 2 performs slightly worst only on mineral, fossil and renewable depletion category if compared with Case 1 and 3 (respectively up to 0.2 % and 6% increase). Case 3, on the other hand, has the lowest impact on ozone depletion, photochemical ozone formation, acidification, marine and terrestrial eutrophication, land use and mineral, fossil and renewable depletion. Conversely, Case 3 has the highest environmental loads on human toxicity, particulate matter, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity and water resource depletion.

In Norway water depletion results follow a different trend compared to the other countries. While in UK, US and Saudi Arabia water depletion is higher in Case 2 compared to Case 3, in Norway results are the opposite. The main contributor to water depletion indicator in UK, US and Saudi Arabia for Cases 2 and 3 is the cooling water. The amount of cooling water consumed in Norway is less than the other countries; moreover, what it significantly changes is the characterization factor that the impact assessment method gives to Norway water. Among the four analysed regions, Norway is the one less affected by water scarcity problems. For this reason, on the overall impact on water depletion, the higher water consumption of cooling water in Case 2 does not affect the results. The main contributor to Norway water depletion impact category is given by the electricity and, in particular, by the water consumed in electricity production processes. Case 3 uses more electricity compared to Case 2 and this explains its higher impact of water depletion impact category.

Table 29. Characterized impacts calculated for UAN synthesis in each case (Norway case study).

Impact category	Unit/FU	Case 1. UAN synthesis, NG w/o CO_2 capt (Norway case)	Case 2. UAN synthesis, NG with CO_2 capt (Norway case)	Case 3. UAN synthesis, hybrid NG/ water electrolysis with CO_2 capt (Norway case)
Climate change	kg CO_2 eq	402.040	144.369	140.388
Ozone depletion	kg CFC-11 eq	5.84E-05	5.96E-05	4.57E-05
Human toxicity, non-cancer effects	CTUh	1.65E-05	1.69E-05	1.79E-05
Human toxicity, cancer effects	CTUh	1.41E-06	1.45E-06	2.05E-06
Particulate matter	kg PM2.5 eq	0.074	0.074	0.083
Ionizing radiation HH	kBq U235 eq	2.201	2.429	11.113
Ionizing radiation E (interim)	CTUe	1.63E-05	1.80E-05	8.25E-05

Impact category	Unit/FU	Case 1. UAN synthesis, NG w/o CO_2 capt (Norway case)	Case 2. UAN synthesis, NG with CO_2 capt (Norway case)	Case 3. UAN synthesis, hybrid NG/ water electrolysis with CO_2 capt (Norway case)
Photochemical ozone formation	kg NMVOC eq	0.934	0.929	0.844
Acidification	molc H+ eq	1.673	1.672	1.642
Terrestrial eutrophication	molc N eq	3.741	3.712	3.436
Freshwater eutrophication	kg P eq	0.003	0.003	0.004
Marine eutrophication	kg N eq	0.287	0.284	0.257
Freshwater ecotoxicity	CTUe	44.292	45.156	55.206
Land use	kg C deficit	377.656	378.305	360.979
Water resource depletion	m^3 water eq	0.121	0.130	0.320
Mineral, fossil & ren resource depletion	kg Sb eq	0.0063	0.0064	0.0062

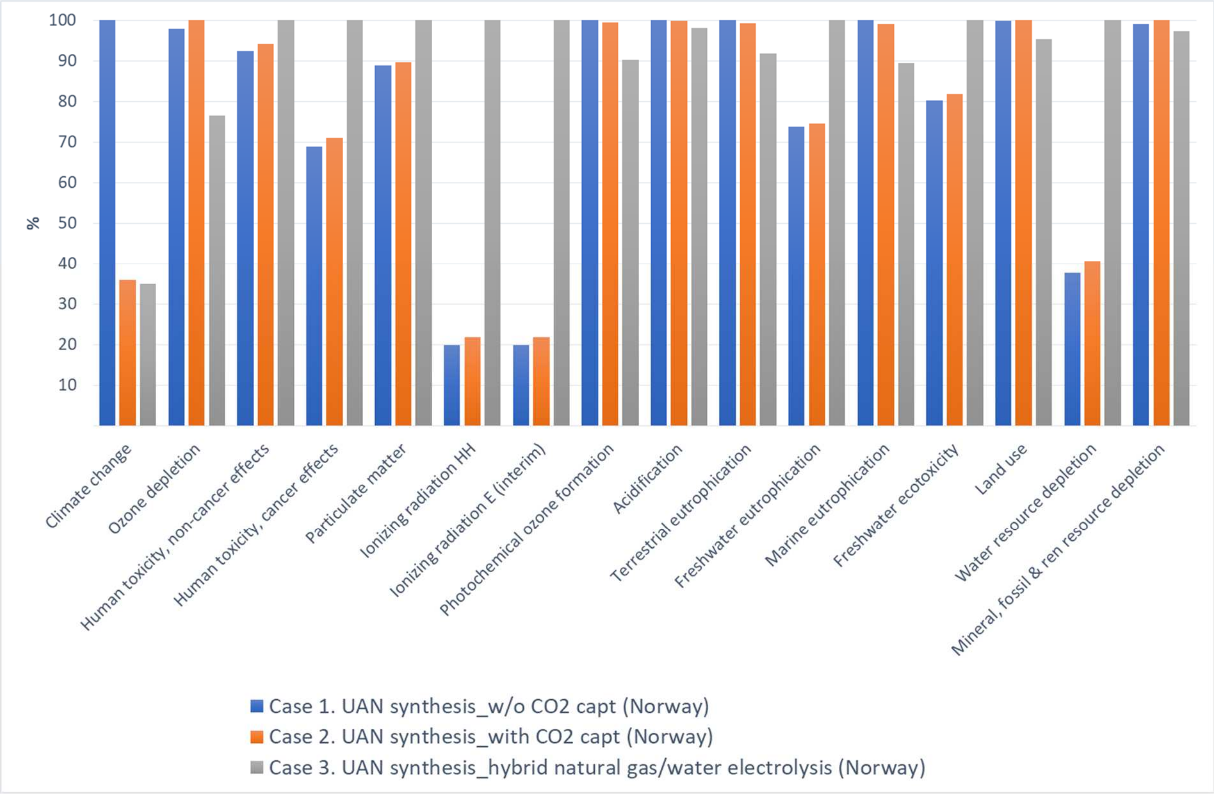

Figure 4. Characterized impacts calculated for UAN synthesis in each case (Norway case study).

With reference to UAN solution production in Norway (table 29), for all cases, the ammonium nitrate solution (ANS) synthesis process has the highest contribution to all environmental impact categories, followed by urea solution 77% production process. Climate change indicator registers the lowest values for the Case 3 (140 kg CO_2 eq/tonne UAN), followed by Case 2 (144 kg CO_2 eq/tonne UAN) and Case 1 (402 kg CO_2 eq/tonne UAN).

As already observed for urea production, the results show a different trend on the rest of environmental indicators. Photochemical ozone formation, acidification, terrestrial and marine eutrophication give the highest values for Case 2. Both Case 1 and Case 2 give lower values for human toxicity, particulate matter, ionizing radiation, freshwater eutrophication, freshwater ecotoxicity and water resource depletion than Case 3.

3.3. Environmental performance of Urea and UAN solution synthesis: the United State case study

Tables 30 and 31 summarize the characterized impacts of 1 tonne of Urea and 1 tonne of UAN 32.0.0 solution (functional units-FU) solution production in United States (US) by three investigated technologies.

Table 30. Characterized impacts calculated for urea synthesis in each case (United States case study).

Impact category	Unit	Case 1. Urea synthesis, NG w/o CO_2 capt (US case)	Case 2. Urea synthesis, NG with CO_2 capt (US case)	Case 3. Urea synthesis, hybrid NG/ water electrolysis with CO_2 capt (US case)
Climate change	kg CO_2 eq	634.419	382.519	1269.404
Ozone depletion	kg CFC-11 eq	1.46E-04	1.48E-04	1.82E-04
Human toxicity, non-cancer effects	CTUh	2.78E-05	2.90E-05	8.17E-05
Human toxicity, cancer effects	CTUh	5.40E-06	5.52E-06	1.02E-05
Particulate matter	kg PM2.5 eq	0.205	0.225	1.088
Ionizing radiation HH	kBq U235 eq	19.822	22.698	152.011
Ionizing radiation E (interim)	CTUe	1.55E-04	1.77E-04	1.19E-03
Photochemical ozone formation	kg NMVOC eq	1.263	1.275	2.369
Acidification	molc H+ eq	2.130	2.187	4.986
Terrestrial eutrophication	molc N eq	3.376	3.410	7.724
Freshwater eutrophication	kg P eq	0.014	0.016	0.107
Marine eutrophication	kg N eq	0.275	0.278	0.641
Freshwater ecotoxicity	CTUe	591.285	596.184	712.502
Land use	kg C deficit	948.666	959.971	1305.905
Water resource depletion	m^3 water eq	16.820	19.690	16.770
Mineral, fossil & ren resource depletion	kg Sb eq	0.003	0.003	0.007

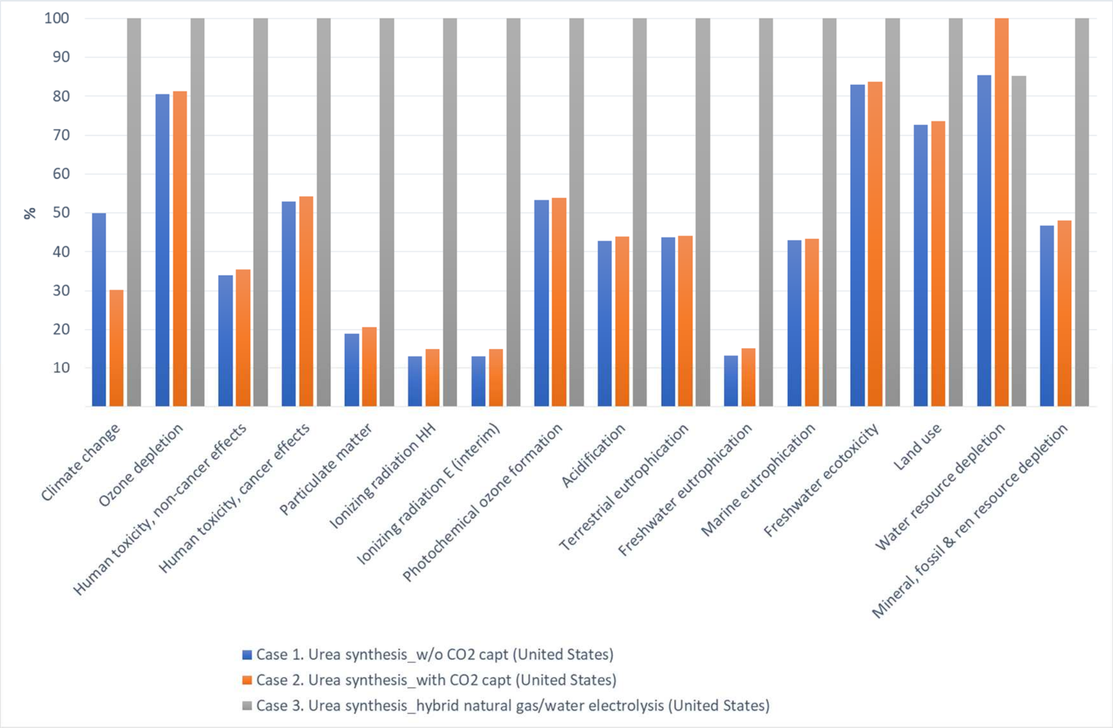

Figure 5. Characterized impacts calculated for urea synthesis in each case (United States case study).

As to the urea granulate production in US, the results in table 30 show that Case 2 has the lowest impact on climate change (releasing 382 kg CO_2 eq/tonne urea) with 40% lower than the benchmark case, i.e. Case 1 (634 kg CO_2 eq/tonne urea). The highest value is obtained in Case 3 (1269 kg CO_2 eq/tonne urea) with about 50% increase over Case 1 and 70% over Case 2. For all cases, the liquid urea production process (synthetized from ammonia precursor) has the highest contribution to the climate change indicator, with an average value of 95% (data not shown), followed by electricity used for granulation process. In particular, about Case 1, ammonia production process-related emissions and natural gas (as feedstock) supply chain determine the largest share of impacts. For Case 2, natural gas (as feedstock) and electricity are the main contributing processes. The major contributor in Case 3 is the hydrogen supply chain, more specifically the electricity production necessary for electrolysis.

Although the climate change for Case 2 has the lowest values amongst the investigated cases, the rest of the environmental impact categories do not follow the same trend. As pictured in figure 5, Case 2 perform slightly worst (up to 15% increase for water resources depletion due to a higher sea/lake water consumption used to accomplish the inter-refrigeration cooling duty of CO_2 compressors) if compared with Case 1. With respect to Case 3, the trend is generally increasing with over 40% in almost all environmental impacts indicators, except for ozone depletion, freshwater ecotoxicity and land use, where the impact does not overcome 26%. Conversely, on water resource depletion category, the impact of Case 3 is reduced (up to 15%) with respect to Case 2 and slightly increased (0.3%) in comparison to Case 1.

Table 31. Characterized impacts calculated for UAN synthesis in each case (United States case study).

Impact category	Unit	Case 1. UAN synthesis, NG w/o CO_2 capt (US case)	Case 2. UAN synthesis, NG with CO_2 capt (US case)	Case 3. UAN synthesis, hybrid NG/ water electrolysis with CO_2 capt (US case)
Climate change	kg CO_2 eq	603.716	371.429	1230.901
Ozone depletion	kg CFC-11 eq	1.37E-04	1.41E-04	1.74E-04
Human toxicity, non-cancer effects	CTUh	2.54E-05	2.72E-05	8.06E-05
Human toxicity, cancer effects	CTUh	4.99E-06	5.23E-06	9.91E-06
Particulate matter	kg PM2.5 eq	0.184	0.206	1.070
Ionizing radiation HH	kBq U235 eq	16.224	19.333	142.741
Ionizing radiation E (interim)	CTUe	1.27E-04	1.51E-04	1.12E-03
Photochemical ozone formation	kg NMVOC eq	1.238	1.278	2.667
Acidification	molc H+ eq	2.091	2.190	5.825
Terrestrial eutrophication	molc N eq	3.060	3.157	8.820
Freshwater eutrophication	kg P eq	0.012	0.014	0.102
Marine eutrophication	kg N eq	0.271	0.279	0.728
Freshwater ecotoxicity	CTUe	554.656	572.905	695.112
Land use	kg C deficit	944.927	977.630	1571.769
Water resource depletion	m^3 water eq	20.374	23.502	21.814
Mineral, fossil & ren resource depletion	kg Sb eq	0.003	0.004	0.010

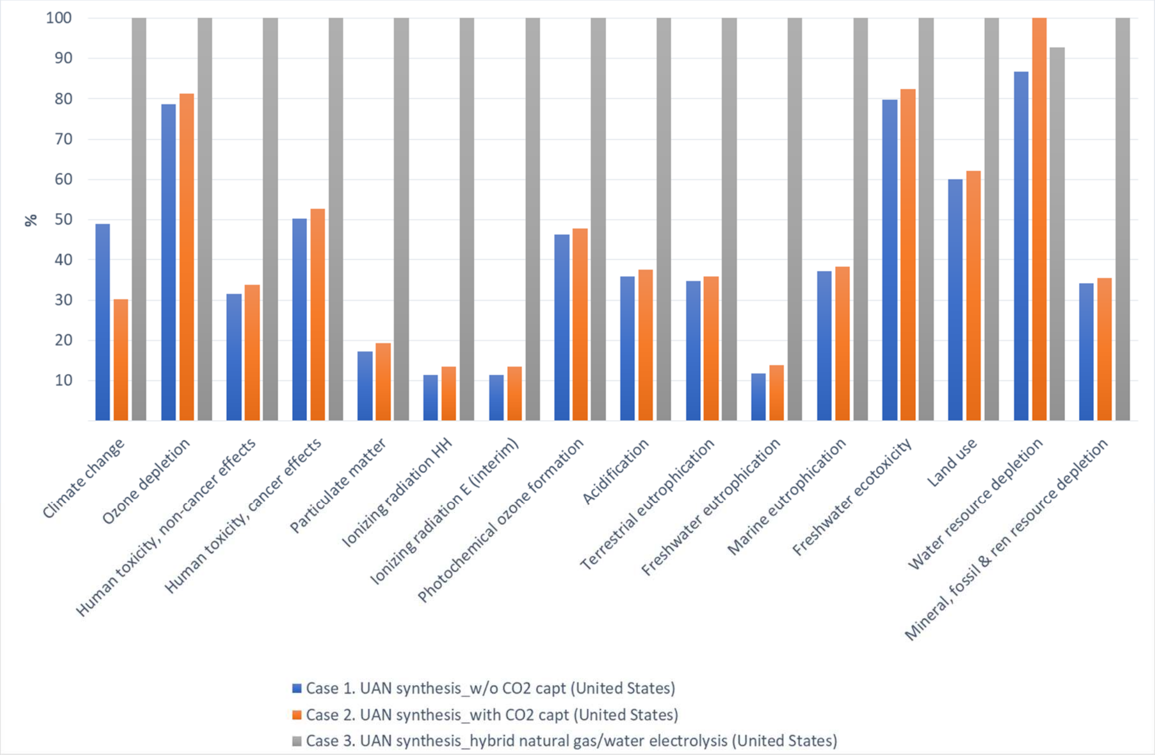

Figure 6. Characterized impacts calculated for UAN synthesis in each case (United States case study).

UAN solution production shows a similar trend in the results compared with urea production (table 31). For all analysed cases, the ammonium nitrate solution (ANS) synthesis process has the highest contribution to all environmental impact categories, followed by urea solution 77% production process. Climate change indicator registers the lowest values for the Case 2 (371 kg CO_2 eq/tonne UAN), followed by Case 1 (604 kg CO_2 eq/tonne UAN) and Case 3 (1231 kg CO_2 eq/tonne UAN).

As already observed for urea production, the results show a different trend on the rest of environmental indicators. Both Case 1 and Case 2 give lower values in almost all environmental impact categories compared to Case 3, except for water resource depletion. In this latter impact category, Case 2 performs worst compared to Case 1 and Case 3, respectively with 13% of impacts above Case 1 and 7% above Case 3.

Case 3 has the worst environmental performance due to the highest specific energy consumption attributable to the electrolyser for hydrogen production (the contribution overcomes 40% in almost all indicators, except for water resource depletion). Natural gas supply chain contributes to environmental impacts for less than 40% while CO_2 capture section and electricity for ammonia synthesis contribute with a share less than 6%.

3.4. Environmental performance of Urea and UAN solution synthesis: the Saudi Arabia case study

Tables 32 and 33 summarize the characterized impacts of 1 tonne of Urea and 1 tonne of UAN 32.0.0 solution (functional units-FU) solution production in Saudi Arabia by three investigated technologies.

Table 32. Characterized impacts calculated for urea synthesis in each case (Saudi Arabia case study).

Impact category	Unit	Case 1. Urea synthesis, NG w/o CO_2 capt (Saudi Arabia case)	Case 2. Urea synthesis, NG with CO_2 capt (Saudi Arabia case)	Case 3. Urea synthesis, hybrid NG/ water electrolysis with CO_2 capt (Saudi Arabia case)
Climate change	kg CO_2 eq	686.301	453.255	2137.544
Ozone depletion	kg CFC-11 eq	1.12E-04	1.17E-04	3.19E-04
Human toxicity, non-cancer effects	CTUh	3.29E-05	3.38E-05	6.82E-05
Human toxicity, cancer effects	CTUh	2.88E-06	2.97E-06	6.27E-06
Particulate matter	kg PM2.5 eq	0.184	0.204	1.086
Ionizing radiation HH	kBq U235 eq	10.709	12.160	74.947
Ionizing radiation E (interim)	CTUe	7.71E-05	8.75E-05	5.33E-04
Photochemical ozone formation	kg NMVOC eq	1.683	1.791	7.033
Acidification	molc H+ eq	2.836	3.095	14.711
Terrestrial eutrophication	molc N eq	5.000	5.354	23.466
Freshwater eutrophication	kg P eq	0.002	0.002	0.005
Marine eutrophication	kg N eq	0.421	0.453	2.104
Freshwater ecotoxicity	CTUe	589.433	613.437	1573.479
Land use	kg C deficit	1139.121	1204.886	3924.700
Water resource depletion	m^3 water eq	37,455.749	43,476.188	33,431.140
Mineral, fossil & ren resource depletion	kg Sb eq	0.003	0.003	0.009

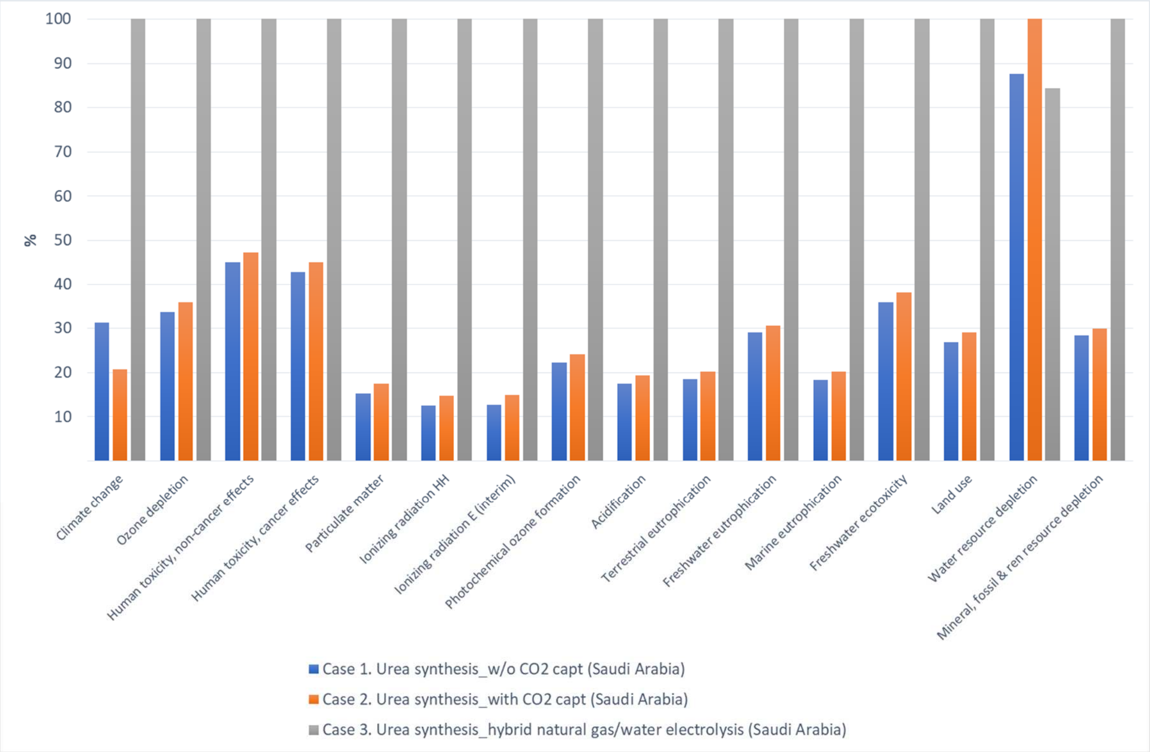

Figure 7. Characterized impacts calculated for urea synthesis in each case (Saudi Arabia case study).

As to the urea granulate production in Saudi Arabia, the results in table 32 show that Case 2 has the lowest impact on climate change (releasing 453 kg CO_2 eq/tonne urea) with 34% lower than the benchmark case, i.e. Case 1 (686 kg CO_2 eq/tonne urea). The highest value is obtained in Case 3 (2,137 kg CO_2 eq/tonne urea) with about 68% increase over Case 1 and 79% over Case 2. For all investigated cases, the liquid urea production process (synthetized from ammonia precursor) has the highest contribution to the climate change indicator, with an average value of 94% (data not shown), followed by electricity used for granulation process. In particular, about Case 1, ammonia production process-related emissions and electricity mix have the largest share of impacts. For Case 2, natural gas (as feedstock) and electricity are the main contributing processes. The major contributor to Case 3 is brought by the hydrogen supply chain, more specifically the electricity production necessary for electrolysis.

Although the climate change for Case 2 has the lowest values amongst the investigated cases, the rest of the environmental impact categories do not follow the same trend. As pictured in figure 7, Case 2 performs worst (up to 12% increase for water resources depletion due to a higher sea/lake water consumption used to accomplish the inter-refrigeration cooling duty of CO_2 compressors) if compared with Case 1. Both Case 1 and Case 2 give lower values for all environmental impacts indicators than Case 3. The trend is generally increasing with over 50% in almost all environmental impacts indicators, except for water resource depletion category, whereas the impact of Case 3 is reduced, up to16 % and 4% respectively in comparison with Case 2 and Case 1.

Table 33. Characterized impacts calculated for UAN synthesis in each case (Saudi Arabia case study).

Impact category	Unit	Case 1. UAN synthesis, NG w/o CO_2 capt (Saudi Arabia case)	Case 2. UAN synthesis, NG with CO_2 capt (Saudi Arabia case)	Case 3. UAN synthesis, hybrid NG/ water electrolysis with CO_2 capt (Saudi Arabia case)
Climate change	kg CO_2 eq	639.488	424.369	2044.936
Ozone depletion	kg CFC-11 eq	1.01E-04	1.08E-04	3.01E-04
Human toxicity, non-cancer effects	CTUh	3.07E-05	3.22E-05	6.83E-05
Human toxicity, cancer effects	CTUh	2.64E-06	2.78E-06	6.18E-06
Particulate matter	kg PM2.5 eq	0.164	0.186	1.069
Ionizing radiation HH	kBq U235 eq	8.922	10.484	70.757
Ionizing radiation E (interim)	CTUe	6.43E-05	7.54E-05	5.04E-04
Photochemical ozone formation	kg NMVOC eq	1.561	1.695	7.038
Acidification	molc H+ eq	2.600	2.896	14.933
Terrestrial eutrophication	molc N eq	4.350	4.768	23.577
Freshwater eutrophication	kg P eq	0.002	0.002	0.007
Marine eutrophication	kg N eq	0.385	0.424	2.099
Freshwater ecotoxicity	CTUe	538.068	572.765	1,499.505
Land use	kg C deficit	1,082.980	1,167.828	4,023.960
Water resource depletion	m^3 water eq	45,656.406	52,155.574	44,820.326
Mineral, fossil & ren resource depletion	kg Sb eq	0.004	0.004	0.013

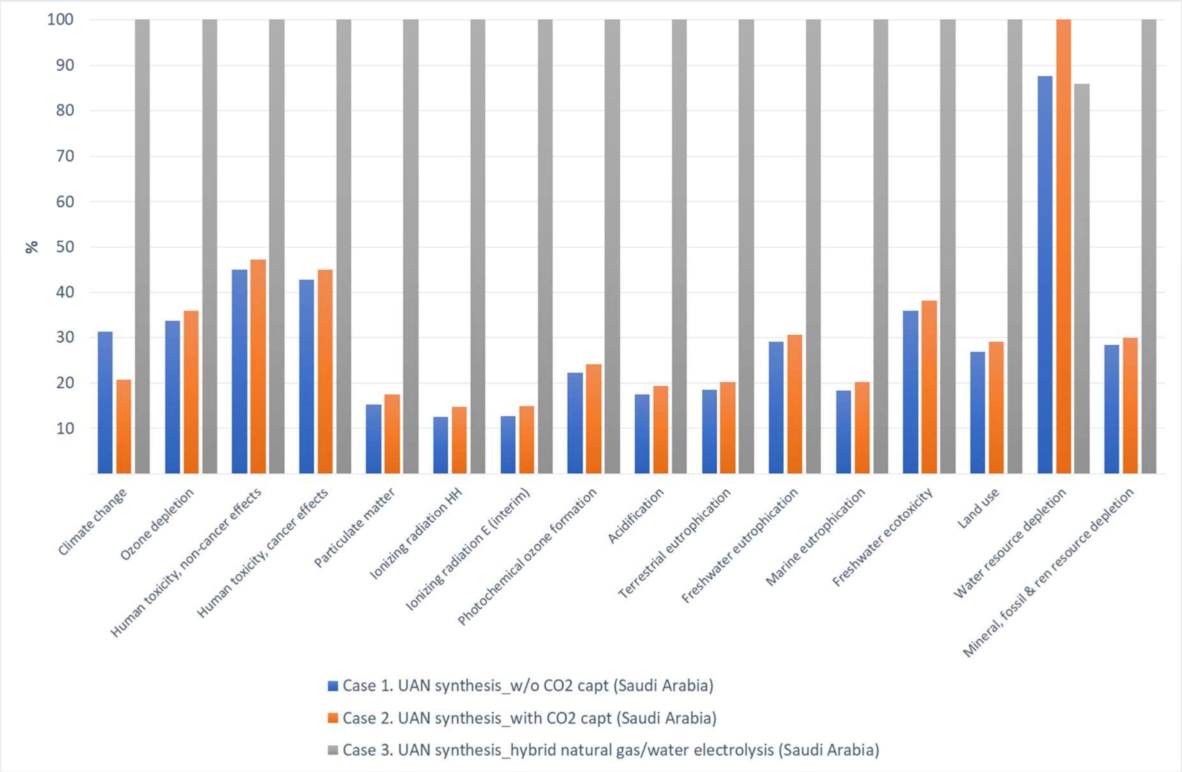

Figure 8. Characterized impacts calculated for UAN synthesis in each case (Saudi Arabia case study).

UAN solution production shows a similar trend in the results compared with urea production (table 33). For all analysed cases, the ammonium nitrate solution (ANS) synthesis process has the highest contribution to all environmental impact categories, followed by urea solution 77% production process. Climate change indicator registers the lowest values for the Case 2 (424 kg CO_2 eq/tonne UAN), followed by Case 1 (639 kg CO_2 eq/tonne UAN) and Case 3 (2,045 kg CO_2 eq/tonne UAN).

The results show a different trend on the rest of environmental indicators. Both Case 1 and Case 2 give lower values in almost all environmental impact categories compared to Case 3, except for water resource depletion. In this latter impact category, Case 2 performs worst compared to Case 1 and Case 3, respectively with 12% of impacts above Case 1 and 14% above Case 3.

Case 3 has the worst environmental performance due to the highest specific energy consumption attributable to the electrolyser for hydrogen production (the contribution overcomes 40% in almost all indicators, except for water resource depletion). Natural gas supply chain contributes to environmental impacts for less than 18% while CO_2 capture section and electricity for ammonia synthesis contribute with a share less than 6%.

3.5. Focus on the ammonia production process: hotspots analysis

LCA results showed that the environmental burden from Urea and UAN fertilizers synthesis arises from production of ammonia precursor. Therefore, in this section a more detailed analysis of the main contributing processes within ammonia synthesis is presented for all investigated cases. As pictured in figures 9, 12, 15, 18, in Case 1 (i.e. benchmark) the CO_2 process emission has the highest contribution to the climate change indicator, sharing 50%-80% greenhouse gases emissions (GHGs) emission. The rest of environmental indicators are mostly affected by the utilization of natural gas as both a raw material and fuel source and the electricity grid mix (in particular ozone depletion, particulate matter, ionizing radiation, eutrophication, land use and mineral and fossil resource depletion indicators). The electricity mix has a low influence on various environmental impact indicators (except for ionizing radiation and water resource depletion) only in Norway case since it comes from non-fossil sources. Process water only shared significant burdens on water resource depletion indicator (up to 75%). Catalysts supply chain has a contribution especially on human toxicity and freshwater ecotoxicity indicators ranging from 20% to 50% (except for Saudi Arabia and US where the contribution on freshwater ecotoxicity is lower than 2%).

Regarding Case 2, the results of figures 10, 13, 16, 19 show that the integration of CO_2 capture unit in the ammonia synthesis route, although the additional energy consumption, has a positive influence on the climate change indicator, showing a significant reduction of CO_2 process emission. This latter result is opposed to Case 1, where process-based emissions are predominant. Burden contributions for natural gas feedstock and electricity consumption account for 20-40% of overall impacts, where ozone depletion, particulate matter, eutrophication, land use and mineral and fossil resource depletion represent the most categories affected. In Norway case the electricity mix has a low influence on almost all the impact categories since the electricity required for the process comes from non-fossil sources. The main contributor to Norway water depletion impact category is given by the electricity and, in particular, by the water consumed in the electricity production process. As for Case 3, as observed in figures 11, 14, 17, 20 the electricity required for hydrogen production from electrolysis is responsible for the largest share with contribution between 20-80% all across impact categories.

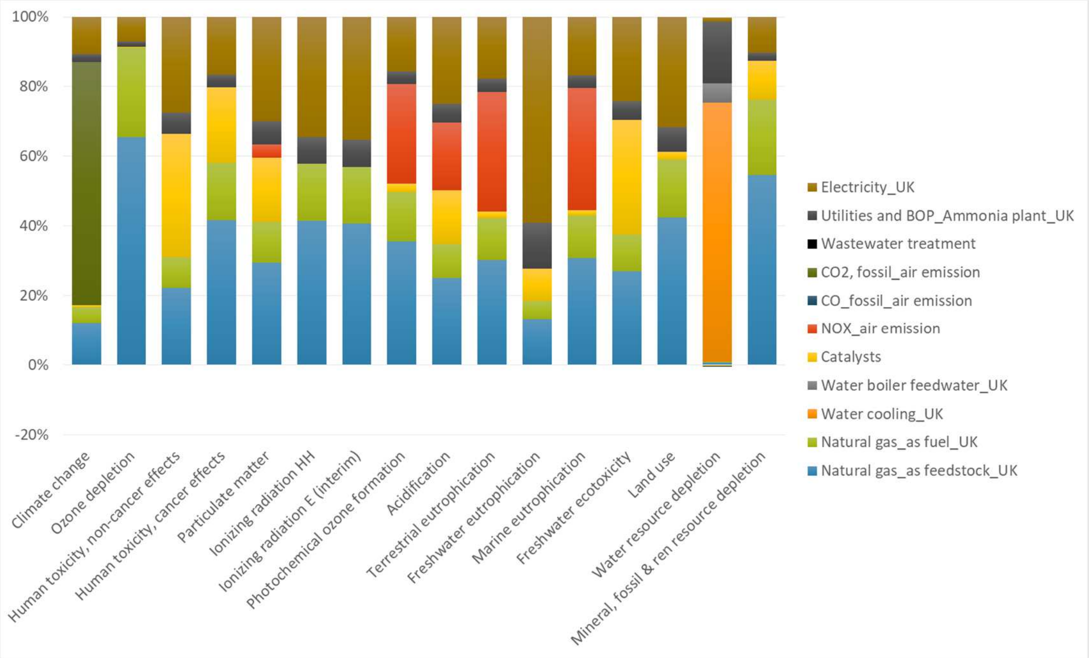

Figure 9. UK Case 1) Production of ammonia from natural gas without CO_2 capture from SMR (Steam Methane Reformer) flue gases. Processes contribution to each impact category.

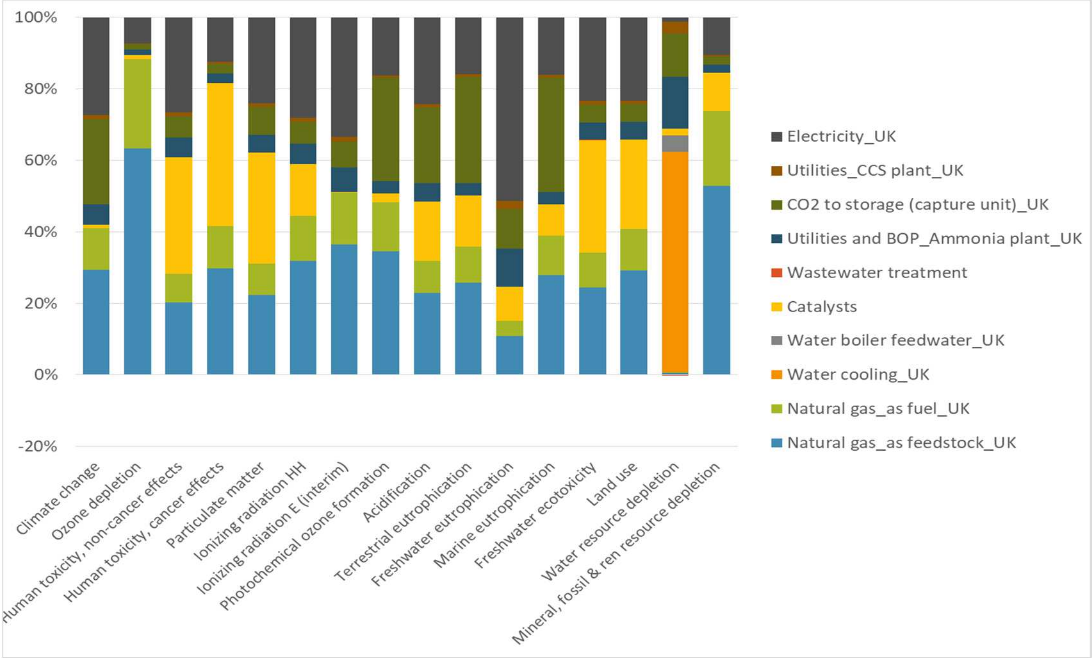

Figure 10. UK Case 2) Production of Ammonia from natural gas with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

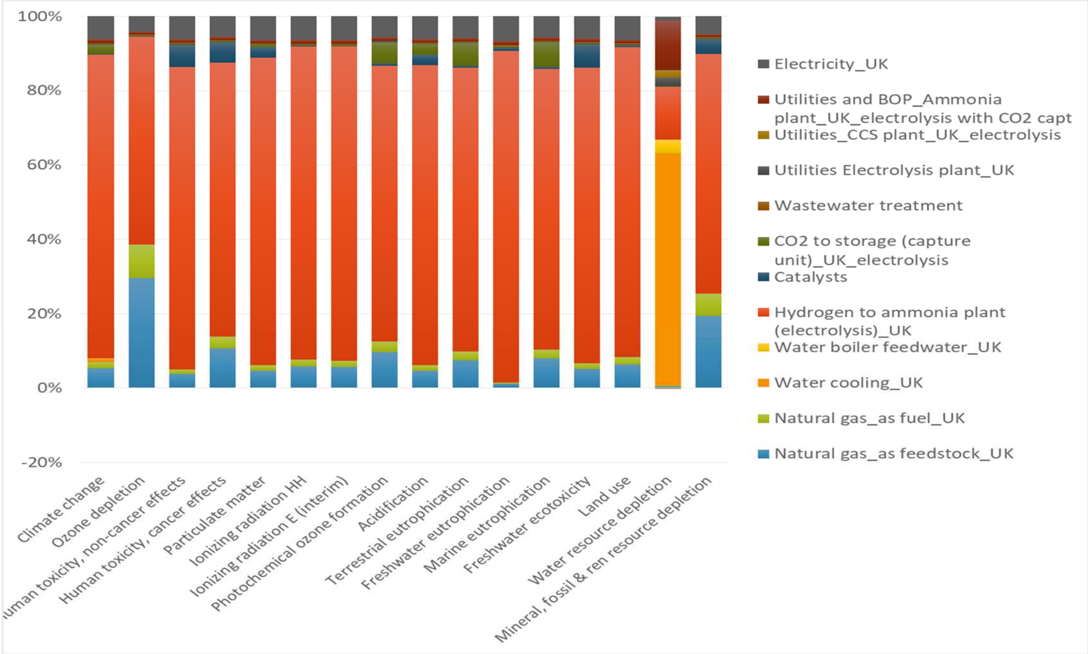

Figure 11. UK Case 3) "Hybrid" production of ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

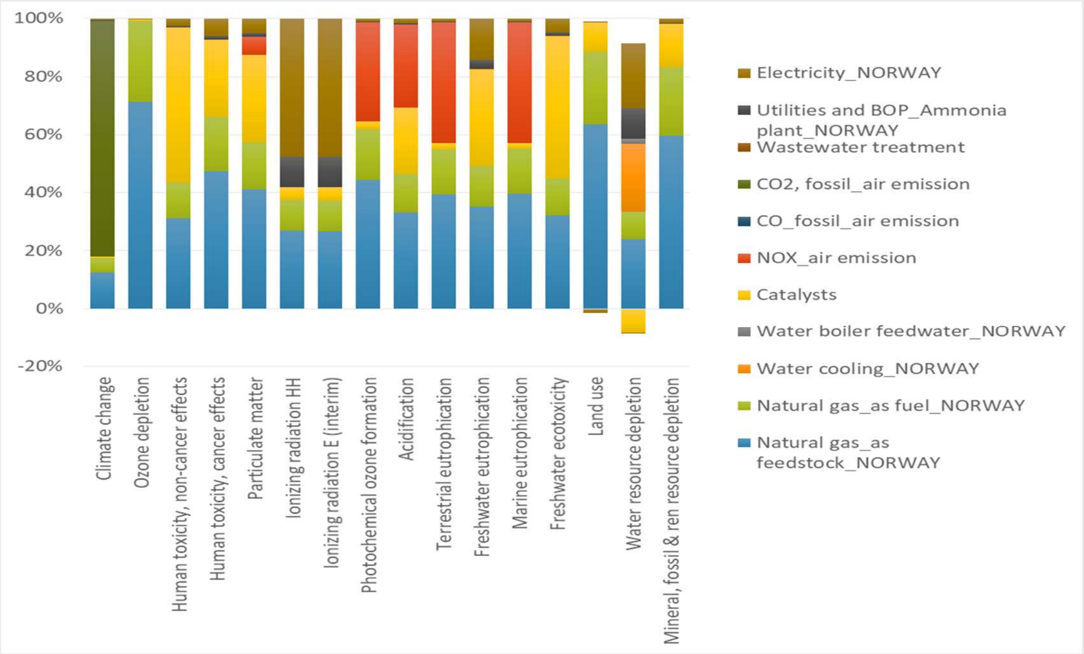

Figure 12. Norway Case 1) Production of ammonia from natural gas without CO_2 capture from SMR (Steam Methane Reformer) flue gases. Processes contribution to each impact category.

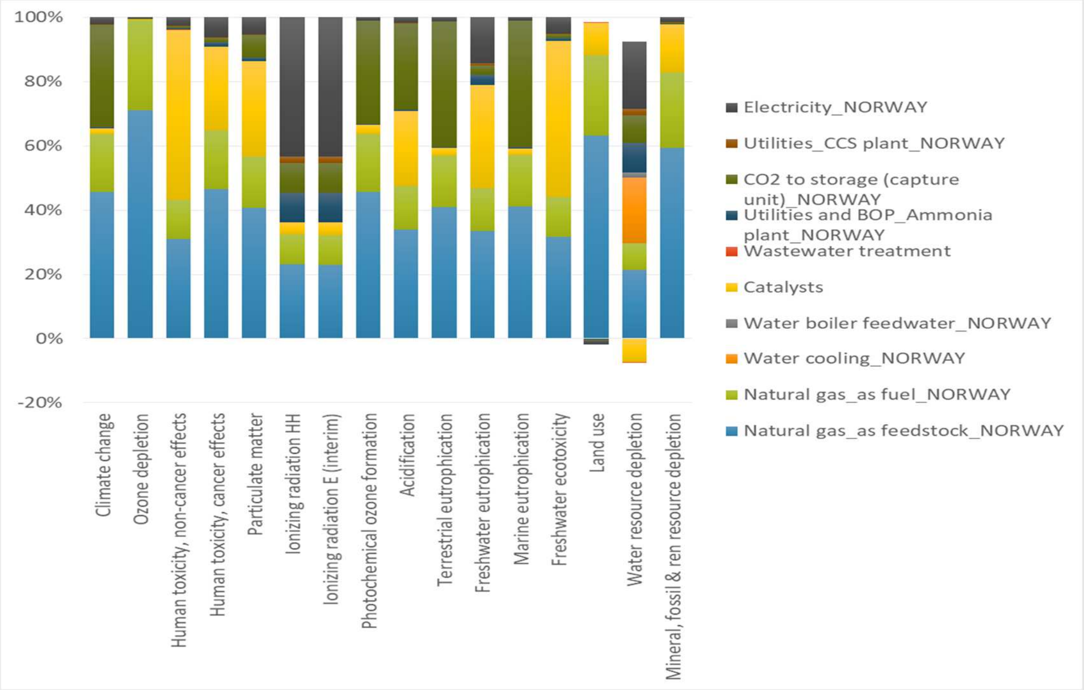

Figure 13. Norway Case 2) Production of Ammonia from natural gas with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

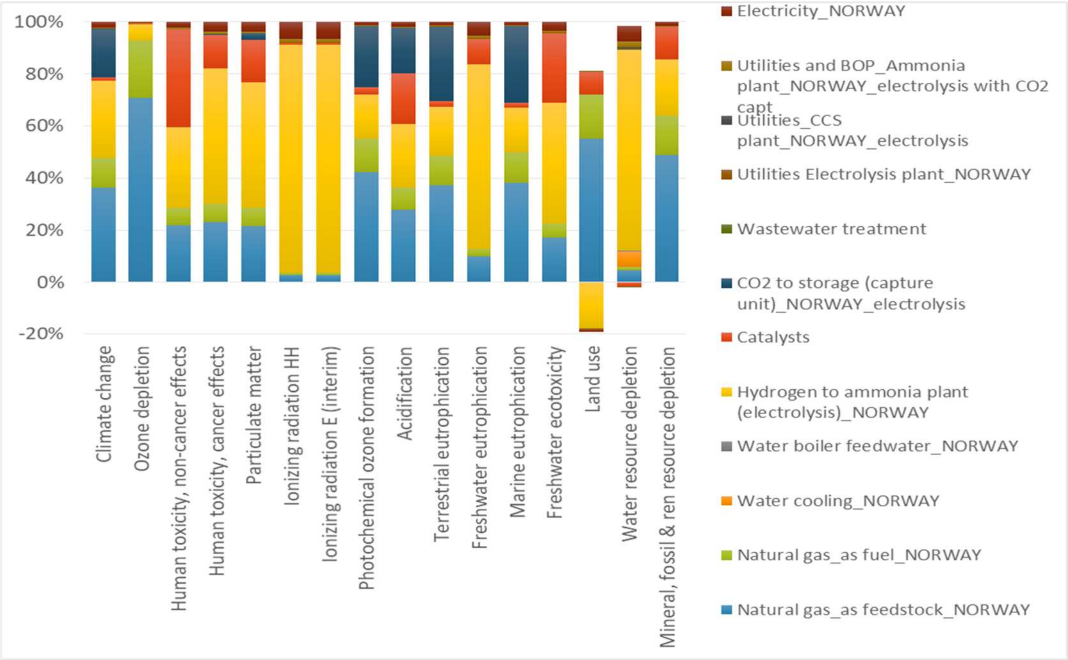

Figure 14. Norway Case 3) "Hybrid" production of ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

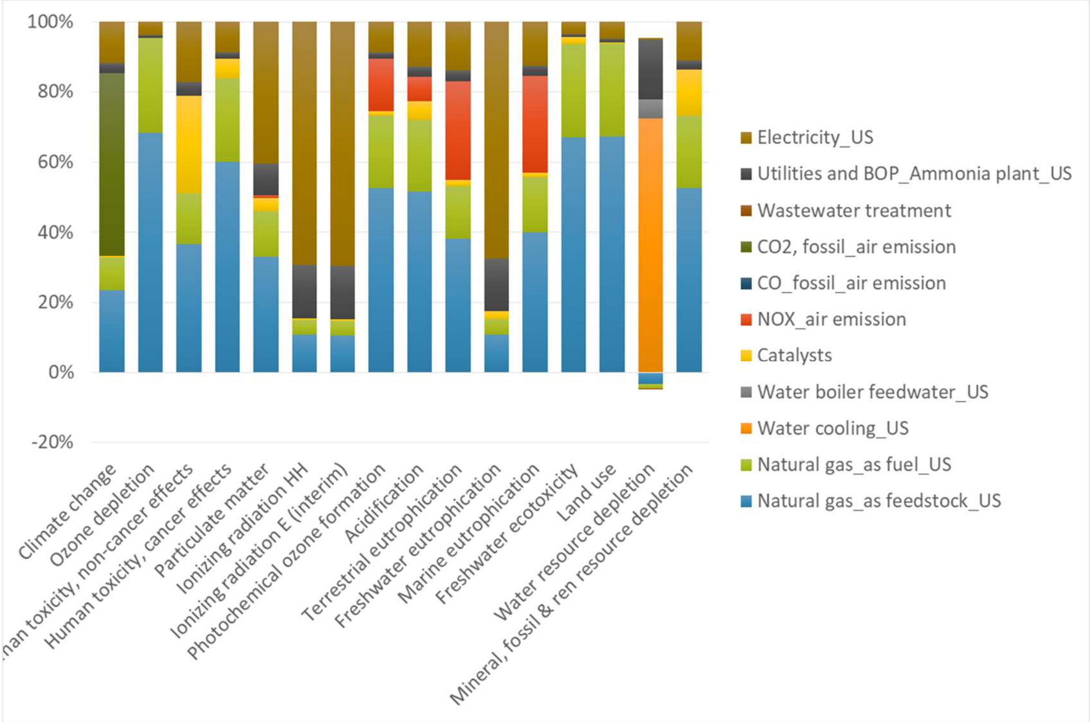

Figure 15. US Case 1) Production of ammonia from natural gas without CO_2 capture from SMR (Steam Methane Reformer) flue gases. Processes contribution to each impact category.

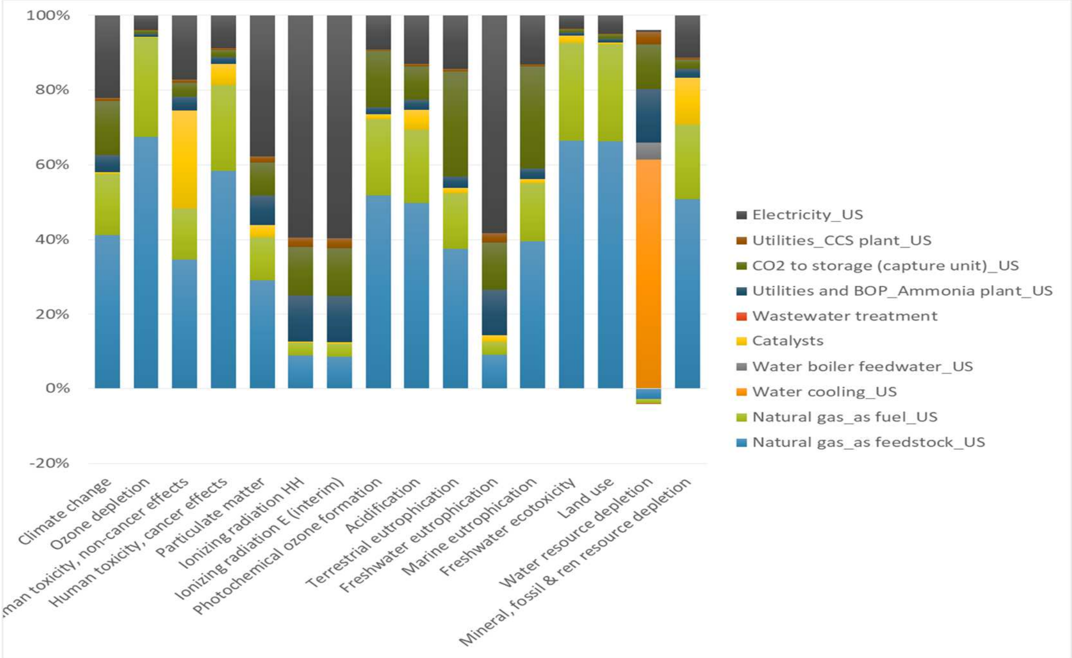

Figure 16. US Case 2) Production of Ammonia from natural gas with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

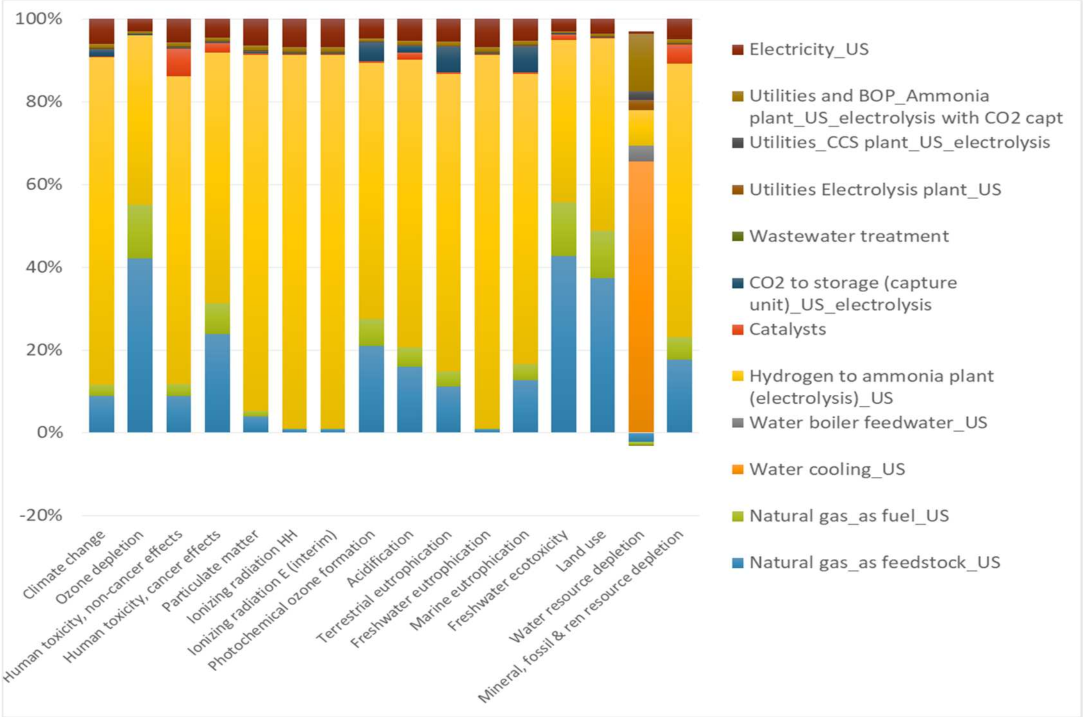

Figure 17. US Case 3) "Hybrid" production of ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

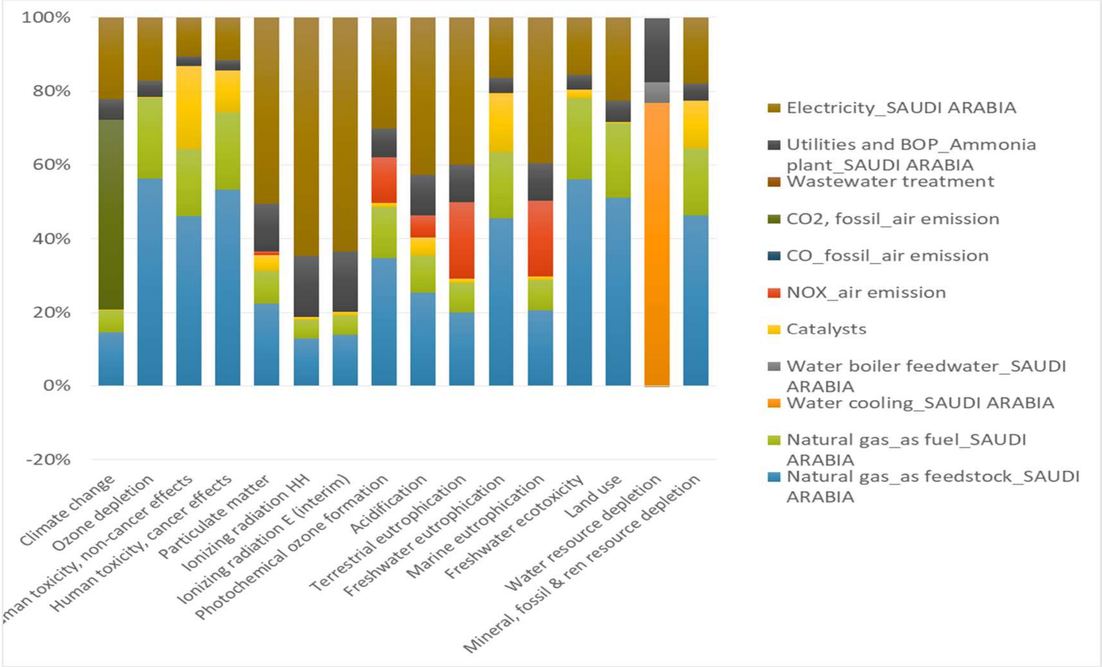

Figure 18. Saudi Arabia Case 1) Production of ammonia from natural gas without CO_2 capture from SMR (Steam Methane Reformer) flue gases. Processes contribution to each impact category

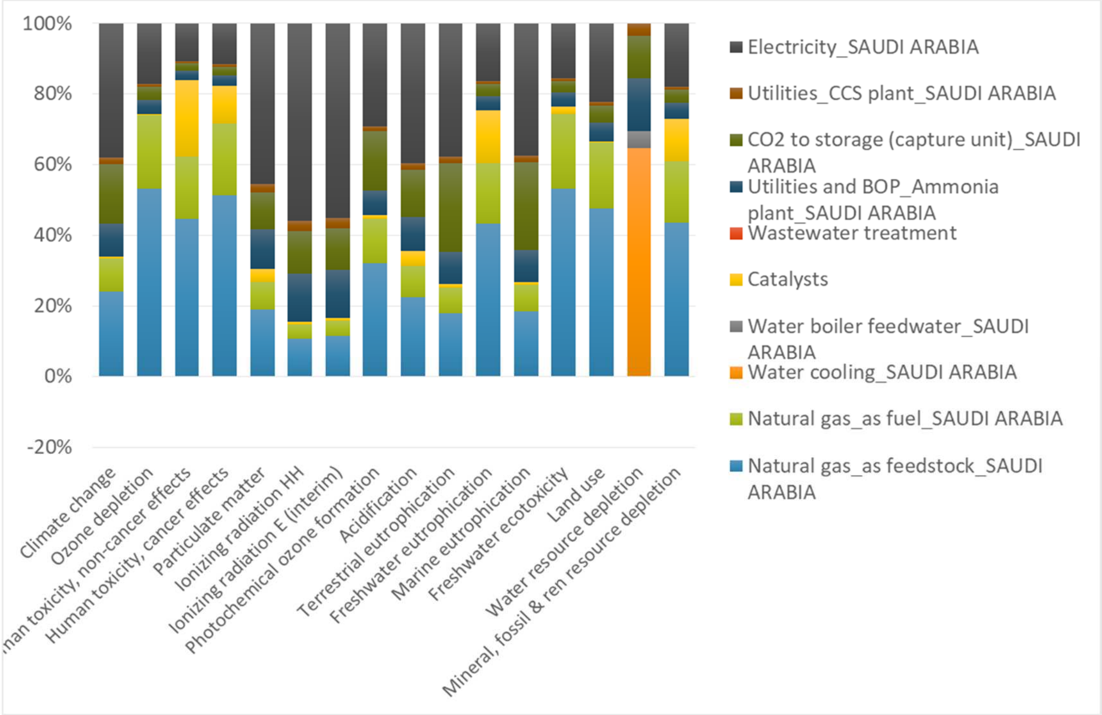

Figure 19. Saudi Arabia Case 2) Production of Ammonia from natural gas with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

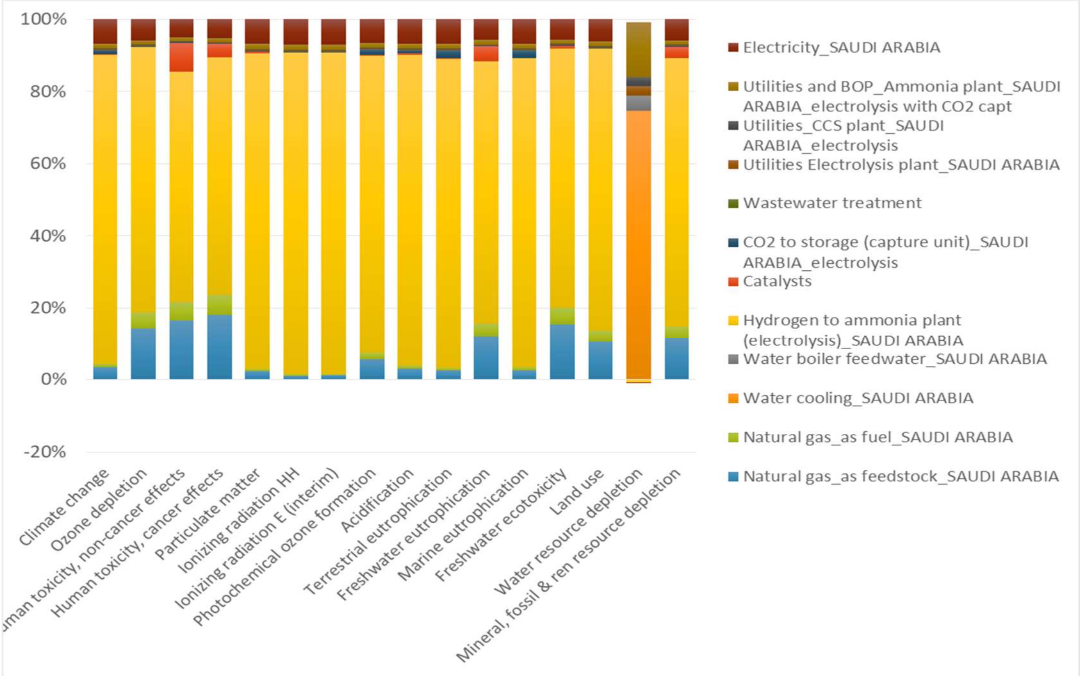

Figure 20. Saudi Arabia Case 3) "Hybrid" production of ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases. Processes contribution to each impact category.

3.6 Environmental profile comparison of fertilizers' production location dependent

As observed in the LCA results section, the electricity consumption is one of the main “hotspot” above the three examined technologies for Urea and UAN 32.0.0 solution production. Electricity mixes have been modelled using Ecoinvent 3.6 database. The shares of electricity technologies in Ecoinvent datasets have been calculated based on IEA World Energy Statistics and Balances. Electricity mixes consider the share of electricity produced in the regions and import and export from and to other countries. Thus, in the following section a direct comparison among four investigated location (UK, Norway, US, Saudi Arabia) where fertilizers are produced is presented. The goal is to see how the use of electricity grid mix (with different shares of renewables/non renewables sources for power generation), for fertilizers’ production affects the results. The results below are referred to the functional unit of 1 tonne of Urea and 1 tonne of UAN solution produced.

3.6.1. Case 1. Urea and UAN 32.0.0 synthesis (natural gas without CO_2 capture)

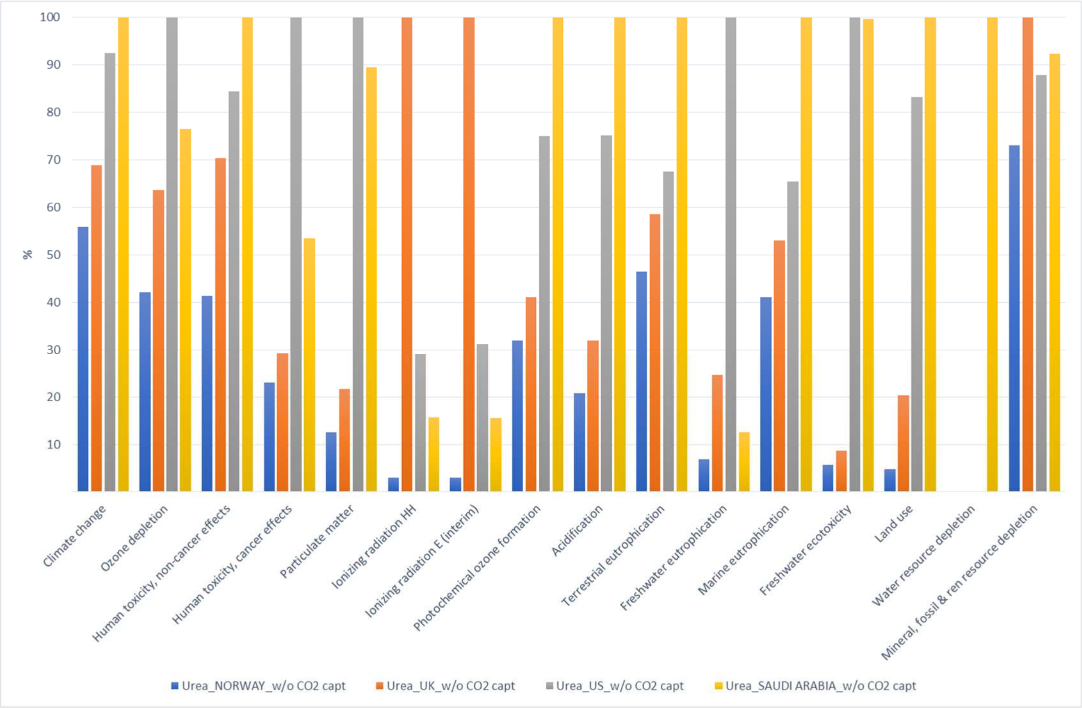

Figure 21. Case 1 - comparison environmental profile for urea synthesis in Norway, UK, US, Saudi Arabia.

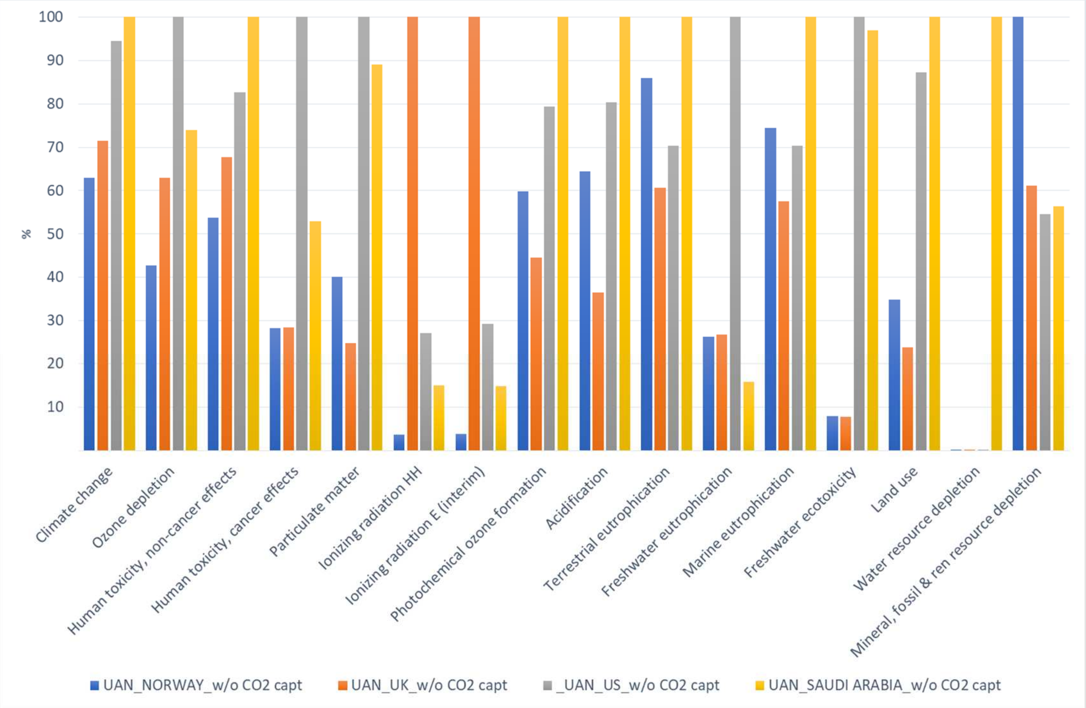

Figure 22. Case 1 - comparison environmental profile for UAN synthesis in Norway, UK, US, Saudi Arabia.

Figures 21 and 22 show the results of the comparison among the different electricity mixes applied during the Urea and UAN solution production without CO_2 capture (i.e. Case 1). As observed in figure 21, the Urea produced in Saudi Arabia gave the highest environmental impacts in 8 out of the 16 investigated impact categories, followed by Urea produced in US (5 out of 16 impact categories) and UK (2 out of 16 impact categories). In contrast, Urea produced in Norway results in the lowest environmental impacts across all indicators. These findings are explained by the fact that the share of renewables in Norway electricity mix is higher than 90%, while in US, UK and Saudi Arabia does not exceed 25% (www.iea.org/data-and-statistics).

Looking at the impact of water resource depletion category, Saudi Arabia case reports the highest values compared with other countries. Water consumption is higher in warmer climates because, even though condensation requires a lower enthalpy drop, the amount of steam expanded to obtain the same power output is substantially higher.

Concerning UAN production, Saudi Arabia gave the highest environmental impacts in 8 out of the 16 investigated impact categories, followed by UAN produced in US (5 out of 16 impact categories) and UK (2 out of 16 impact categories). Conversely, UAN produced in Norway presents lowest values for 9 out 16 environmental impact indicators.

3.6.2 Case 2. Urea and UAN 32.0.0 synthesis (natural gas with CO_2 capture)

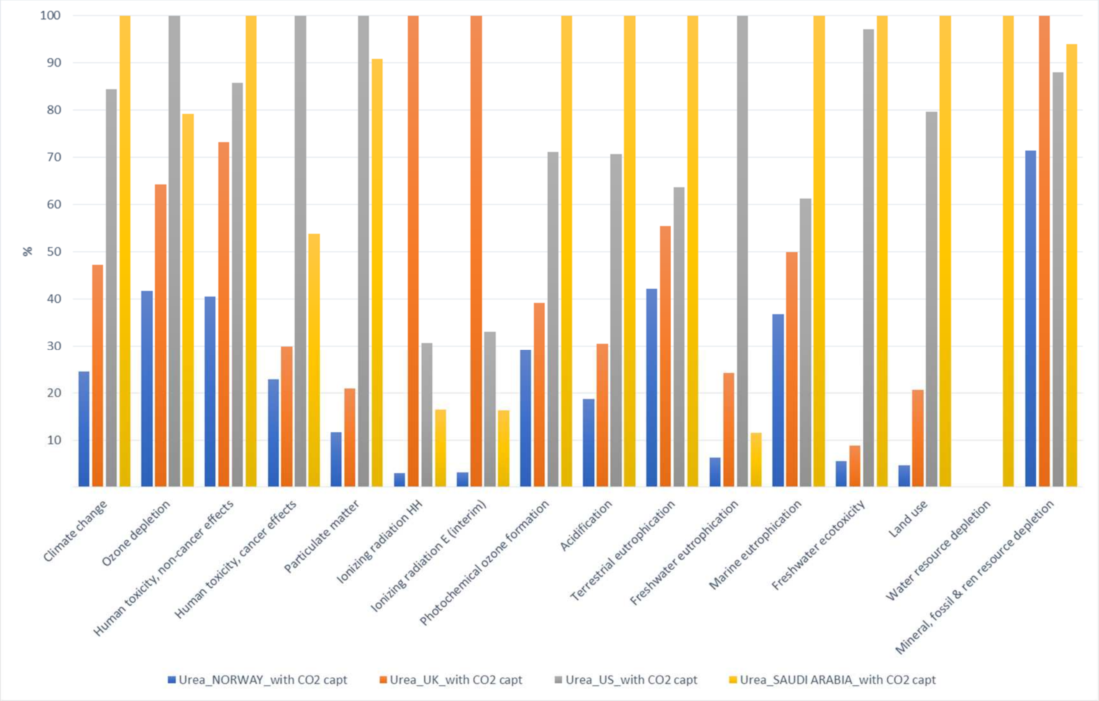

Figure 23. Case 2 - comparison environmental profile for urea synthesis in Norway, UK, US, Saudi Arabia.

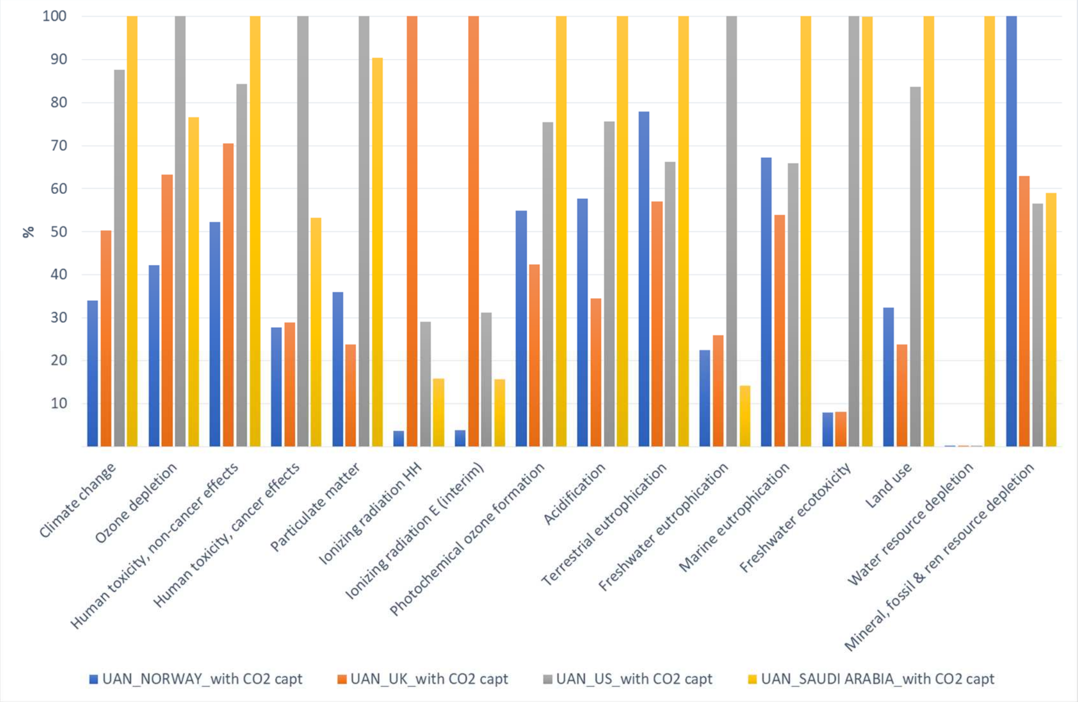

Figure 24. Case 2 - comparison environmental profile for UAN synthesis in Norway, UK, US, Saudi Arabia.

Figures 23 and 24 show the results of the comparison among the different electricity mixes applied during the Urea and UAN solution production with CO_2 capture (i.e. Case 2). As observed in figure 23, the Urea produced in Saudi Arabia gave the highest environmental impacts in 9 out of the 16 investigated impact categories, followed by Urea produced in US (4 out of 16 impact categories) and UK (3 out of 16 impact categories). In contrast, Urea produced in Norway results in the lowest environmental impacts across all indicators.

Looking at the impact of water resource depletion category, Saudi Arabia case reports the highest values compared with other countries.

Concerning UAN production, Saudi Arabia gave the highest environmental impacts in 9 out of the 16 investigated impact categories, followed by UAN produced in US (5 out of 16 impact categories) and UK (2 out of 16 impact categories). Conversely, UAN produced in Norway presents lowest values for 9 out 16 environmental impact indicators.

3.6.3 Case 3. Urea and UAN 32.0.0 synthesis (hybrid NG/water electrolysis with CO_2 capture)

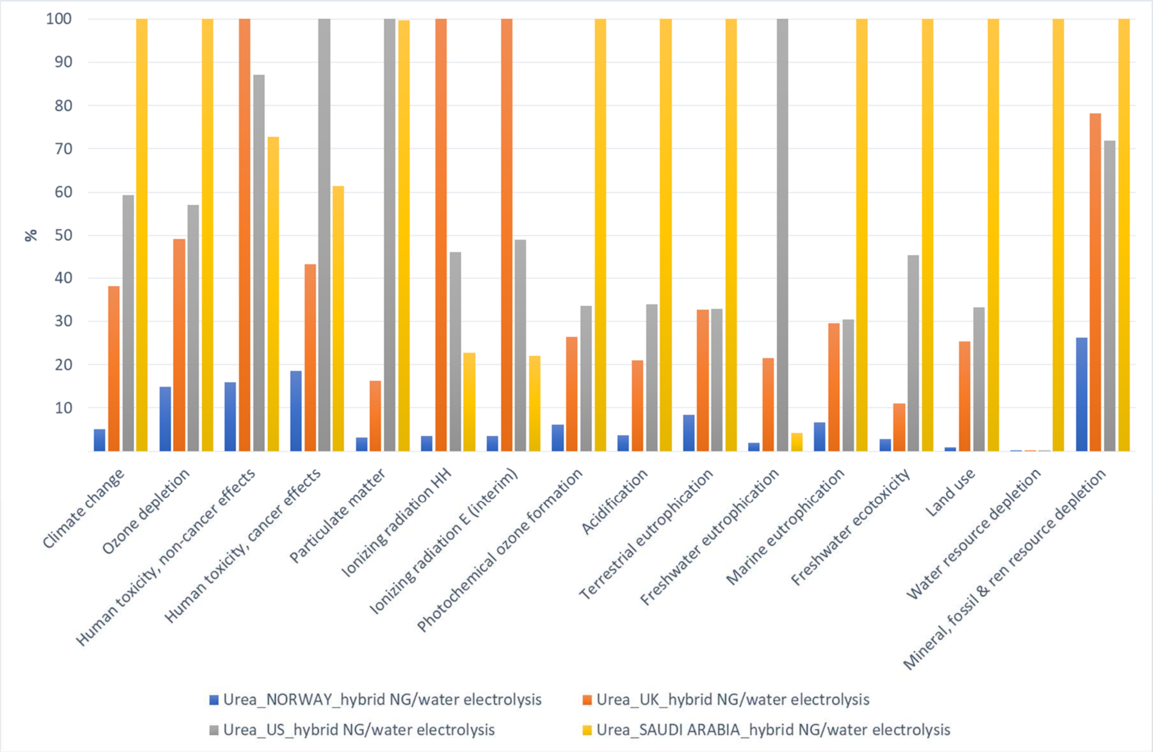

Figure 25. Case 3 - comparison environmental profile for urea synthesis in Norway, UK, US, Saudi Arabia.

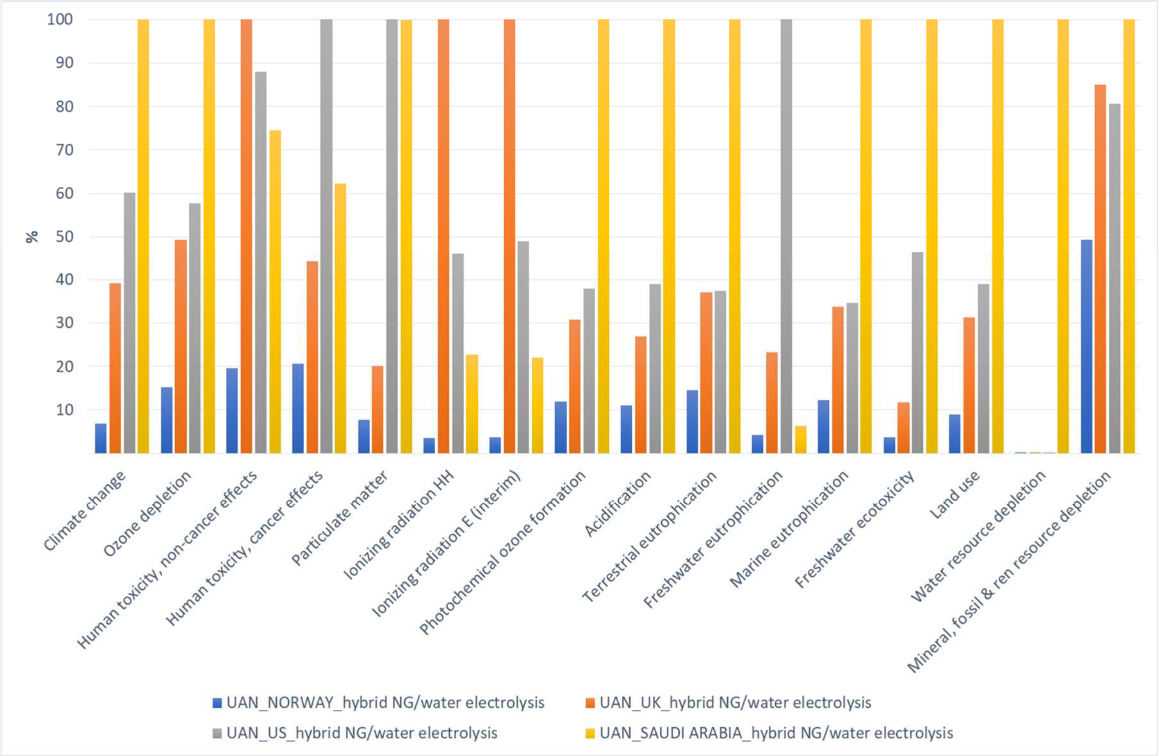

Figure 26. Case 3 - comparison environmental profile for UAN synthesis in Norway, UK, US, Saudi Arabia.

Figures 25 and 26 show the results of the comparison among the different electricity mixes applied during the Urea and UAN solution production with hybrid natural gas/water electrolysis (i.e. Case 3). As observed in figure 25, the Urea produced in Saudi Arabia gave the highest environmental impacts in 10 out of the 16 investigated impact categories, followed by Urea produced in US (3 out of 16 impact categories) and UK (3 out of 16 impact categories). In contrast, Urea produced in Norway results in the lowest environmental impacts across all indicators.

Looking at the impact of water resource depletion category, Saudi Arabia case reports the highest values compared with other countries.

Concerning UAN production, Saudi Arabia gave the highest environmental impacts in 10 out of the 16 investigated impact categories, followed by UAN produced in US (3 out of 16 impact categories) and UK (3 out of 16 impact categories). In opposition, UAN produced in Norway presents lowest values for 9 out 16 environmental impact indicators.

As the results of the rest of impact categories please refer to tables in sections 3.1, 3.2, 3.3, 3.4.

Table 34. Case 1- LCA results for climate change category.

Case 1. Urea and UAN 32.0.0 solution synthesis (natural gas without CO_2 capture)									
Impact category	**Unit/ FU**	**Urea Norway**	**Urea United Kingdom**	**Urea United States**	**Urea Saudi Arabia**	**UAN Norway**	**UAN United Kingdom**	**UAN United States**	**UAN Saudi Arabia**
Climate change	kg CO_2 eq	383	473	634	686	402	457	604	639

Table 35. Case 2 – LCA results for climate change category.

Case 2. Urea and UAN 32.0.0 solution synthesis (natural gas with CO_2 capture)									
Impact category	**Unit/ FU**	**Urea Norway**	**Urea United Kingdom**	**Urea United States**	**Urea Saudi Arabia**	**UAN Norway**	**UAN United Kingdom**	**UAN United States**	**UAN Saudi Arabia**
Climate change	kg CO_2 eq	111	214	383	453	144	213	371	424

Table 36. Case 3 – LCA results for climate change category.

Case 3. Urea and UAN 32.0.0 solution synthesis (hybrid natural gas/water electrolysis with CO_2 capture)									
Impact category	**Unit/ FU**	**Urea Norway**	**Urea United Kingdom**	**Urea United States**	**Urea Saudi Arabia**	**UAN Norway**	**UAN United Kingdom**	**UAN United States**	**UAN Saudi Arabia**
Climate change	kg CO_2 eq	108	814	1,269	2,138	140	802	1,231	2,045

3.7 Normalization and weighting

The identification of the most significant impact categories, based on the normalized and weighted results, has an essential role to ensure that the focus is put on those aspects that matter the most. Normalization and weighting are the optional final steps in Life Cycle Impact Assessment (LCIA), after classification and characterisation. Normalization is a procedure used to express the characterized impacts indicators in a way that allows comparison to each other. Normalization standardizes the indicators by dividing their characterized values by a selected reference value, translating into an assessment of how much the investigated process contributes to a given category with reference to a value considered acceptable or unavoidable in a given point in space and time.

Weighting entails multiplying the normalised results of each of the impact categories with a weighting factor that expresses the relative importance of the impact category. The weighted results all have the same unit and can be added up to create one single score for the environmental impact of a product or case.

Weighting results are below presented (tables 37:42) excluding three toxicity related impact categories (human toxicity cancer, human toxicity non-cancer and freshwater ecotoxicity).

The most relevant impact categories have been identified as all impact categories that cumulatively contribute to at least 80% of the total environmental impact.

Table 37. Normalized and weighted results for case 1 “Urea and UAN 32.0.0 solution synthesis (natural gas without CO_2 capture)”.

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Total	Pt	1.33E-01	2.76E-01	5.27E-01	4.60E+02	2.42E-01	2.77E-01	5.56E-01	5.61E+02
Climate change	Pt	4.16E-02	5.13E-02	6.88E-02	7.44E-02	4.36E-02	4.96E-02	6.55E-02	6.94E-02
Ozone depletion	Pt	2.86E-03	4.32E-03	6.78E-03	5.19E-03	2.70E-03	3.98E-03	6.33E-03	4.68E-03
Particulate matter	Pt	6.81E-03	1.17E-02	5.40E-02	4.83E-02	1.94E-02	1.20E-02	4.84E-02	4.31E-02
Ionizing radiation HH	Pt	1.80E-03	6.04E-02	1.75E-02	9.48E-03	1.95E-03	5.29E-02	1.44E-02	7.90E-03
Ionizing radiation E (interim)	Pt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Photochemical ozone formation	Pt	1.70E-02	2.18E-02	3.98E-02	5.31E-02	2.95E-02	2.20E-02	3.91E-02	4.92E-02
Acidification	Pt	1.25E-02	1.92E-02	4.50E-02	6.00E-02	3.54E-02	2.00E-02	4.42E-02	5.50E-02
Terrestrial eutrophication	Pt	1.32E-02	1.66E-02	1.92E-02	2.84E-02	2.13E-02	1.50E-02	1.74E-02	2.47E-02

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Freshwater eutrophication	Pt	6.66E-04	2.38E-03	9.64E-03	1.22E-03	2.14E-03	2.18E-03	8.12E-03	1.29E-03
Marine eutrophication	Pt	1.02E-02	1.32E-02	1.63E-02	2.49E-02	1.70E-02	1.31E-02	1.60E-02	2.28E-02
Land use	Pt	7.38E-04	3.09E-03	1.27E-02	1.52E-02	5.05E-03	3.45E-03	1.26E-02	1.45E-02
Water resource depletion	Pt	3.18E-04	3.69E-02	2.07E-01	4.60E+02	1.48E-03	4.48E-02	2.50E-01	5.61E+02
Mineral. fossil & ren resource depletion	Pt	2.54E-02	3.47E-02	3.05E-02	3.20E-02	6.24E-02	3.82E-02	3.41E-02	3.52E-02

Table 38. Most significant impact categories (highlighted in yellow) for case 1 "Urea and UAN 32.0.0 solution synthesis (natural gas without CO_2 capture)".

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Total	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Climate change	%	31.24	18.61	13.06	0.02	18.03	17.88	11.77	0.01
Ozone depletion	%	2.15	1.57	1.29	0.00	1.12	1.44	1.14	0.00
Particulate matter	%	5.12	4.23	10.25	0.01	8.03	4.34	8.69	0.01
Ionizing radiation HH	%	1.35	21.92	3.33	0.00	0.81	19.09	2.58	0.00
Ionizing radiation E (interim)	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Photochemical ozone formation	%	12.79	7.91	7.56	0.01	12.18	7.93	7.02	0.01
Acidification	%	9.37	6.96	8.55	0.01	14.62	7.23	7.95	0.01
Terrestrial eutrophication	%	9.94	6.04	3.64	0.01	8.79	5.40	3.13	0.00
Freshwater eutrophication	%	0.50	0.86	1.83	0.00	0.89	0.78	1.46	0.00
Marine eutrophication	%	7.70	4.80	3.09	0.01	7.02	4.73	2.88	0.00
Land use	%	0.55	1.12	2.41	0.00	2.09	1.24	2.27	0.00

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Water resource depletion	%	0.24	13.40	39.22	99.92	0.61	16.17	44.99	99.94
Mineral. fossil & ren resource depletion	%	19.06	12.58	5.78	0.01	25.82	13.77	6.13	0.01

Table 39. Normalized and weighted results for case 2 “Urea and UAN 32.0.0 solution synthesis (natural gas with CO_2 capture)”.

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Total	Pt	1.02E-01	2.62E-01	5.47E-01	5.34E+02	2.15E-01	2.69E-01	5.86E-01	6.41E+02
Climate change	Pt	1.20E-02	2.32E-02	4.15E-02	4.92E-02	1.57E-02	2.32E-02	4.03E-02	4.60E-02
Ozone depletion	Pt	2.85E-03	4.40E-03	6.84E-03	5.42E-03	2.76E-03	4.14E-03	6.54E-03	5.01E-03
Particulate matter	Pt	6.85E-03	1.24E-02	5.91E-02	5.37E-02	1.96E-02	1.29E-02	5.43E-02	4.91E-02
Ionizing radiation HH	Pt	1.97E-03	6.55E-02	2.01E-02	1.08E-02	2.15E-03	5.89E-02	1.71E-02	9.28E-03
Ionizing radiation E (interim)	Pt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Photochemical ozone formation	Pt	1.65E-02	2.22E-02	4.02E-02	5.65E-02	2.93E-02	2.27E-02	4.03E-02	5.35E-02
Acidification	Pt	1.22E-02	2.00E-02	4.62E-02	6.54E-02	3.53E-02	2.11E-02	4.63E-02	6.12E-02
Terrestrial eutrophication	Pt	1.28E-02	1.69E-02	1.94E-02	3.04E-02	2.11E-02	1.55E-02	1.79E-02	2.71E-02
Freshwater eutrophication	Pt	6.85E-04	2.66E-03	1.10E-02	1.26E-03	2.17E-03	2.49E-03	9.60E-03	1.35E-03
Marine eutrophication	Pt	9.86E-03	1.34E-02	1.64E-02	2.68E-02	1.68E-02	1.35E-02	1.65E-02	2.51E-02
Land use	Pt	7.35E-04	3.32E-03	1.28E-02	1.61E-02	5.06E-03	3.72E-03	1.31E-02	1.56E-02
Water resource depletion	Pt	4.21E-04	4.30E-02	2.42E-01	5.34E+02	1.60E-03	5.14E-02	2.89E-01	6.41E+02
Mineral. fossil & ren resource depletion	Pt	2.54E-02	3.56E-02	3.13E-02	3.34E-02	6.30E-02	3.97E-02	3.56E-02	3.72E-02

Table 40. Most significant impact categories (highlighted in yellow) for case 2 “Urea and UAN 32.0.0 solution synthesis (natural gas with CO_2 capture)”.

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Total	%	100,00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Climate change	%	11.76	8.84	7.59	0.01	7.30	8.61	6.87	0.01
Ozone depletion	%	2.79	1.68	1.25	0.00	1.29	1.54	1.12	0.00
Particulate matter	%	6.69	4.72	10.80	0.01	9.12	4.81	9.26	0.01
Ionizing radiation HH	%	1.93	24.96	3.67	0.00	1.00	21.88	2.92	0.00
Ionizing radiation E (interim)	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Photochemical ozone formation	%	16.12	8.44	7.36	0.01	13.67	8.44	6.87	0.01
Acidification	%	11.94	7.61	8.45	0.01	16.48	7.83	7.90	0.01
Terrestrial eutrophication	%	12.53	6.43	3.54	0.01	9.83	5.74	3.06	0.00
Freshwater eutrophication	%	0.67	1.01	2.01	0.00	1.01	0.92	1.64	0.00
Marine eutrophication	%	9.63	5.11	3.01	0.01	7.84	5.02	2.82	0.00
Land use	%	0.72	1.26	2.35	0.00	2.36	1.38	2.23	0.00
Water resource depletion	%	0.41	16.39	44.24	99.93	0.74	19.09	49.25	99.95
Mineral. fossil & ren resource depletion	%	24.82	13.55	5.73	0.01	29.36	14.74	6.07	0.01

Table 41. Normalized and weighted results for case 3 “Urea and UAN 32.0.0 solution synthesis (hybrid natural/water electrolysis with CO_2 capture)”.

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Total	Pt	1.07E-01	7.77E-01	1.19E+00	4.12E+02	2.18E-01	8.59E-01	1.31E+00	5.52E+02
Climate change	Pt	1.17E-02	8.83E-02	1.38E-01	2.32E-01	1.52E-02	8.69E-02	1.34E-01	2.22E-01
Ozone depletion	Pt	2.20E-03	7.25E-03	8.42E-03	1.48E-02	2.12E-03	6.87E-03	8.04E-03	1.39E-02
Particulate matter	Pt	9.26E-03	4.66E-02	2.86E-01	2.86E-01	2.18E-02	5.68E-02	2.82E-01	2.81E-01
Ionizing radiation HH	Pt	1.01E-02	2.92E-01	1.35E-01	6.63E-02	9.83E-03	2.74E-01	1.26E-01	6.26E-02
Ionizing radiation E (interim)	Pt	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Photochemical ozone formation	Pt	1.38E-02	5.85E-02	7.47E-02	2.22E-01	2.66E-02	6.84E-02	8.41E-02	2.22E-01
Acidification	Pt	1.16E-02	6.52E-02	1.05E-01	3.11E-01	3.47E-02	8.49E-02	1.23E-01	3.16E-01
Terrestrial eutrophication	Pt	1.13E-02	4.36E-02	4.39E-02	1.33E-01	1.95E-02	4.98E-02	5.01E-02	1.34E-01
Freshwater eutrophication	Pt	1.46E-03	1.56E-02	7.23E-02	3.06E-03	2.91E-03	1.61E-02	6.92E-02	4.42E-03
Marine eutrophication	Pt	8.22E-03	3.68E-02	3.79E-02	1.24E-01	1.52E-02	4.19E-02	4.31E-02	1.24E-01
Land use	Pt	4.96E-04	1.34E-02	1.75E-02	5.25E-02	4.83E-03	1.69E-02	2.10E-02	5.38E-02
Water resource depletion	Pt	2.86E-03	3.90E-02	2.06E-01	4.11E+02	3.93E-03	5.03E-02	2.68E-01	5.51E+02
Mineral. fossil & ren resource depletion	Pt	2.38E-02	7.10E-02	6.53E-02	9.08E-02	6.13E-02	1.06E-01	1.00E-01	1.24E-01

Table 42. Most significant impact categories (highlighted in yellow) for case 3 “Urea and UAN 32.0.0 solution synthesis (hybrid natural gas/water electrolysis with CO_2 capture)”.

Impact category	Unit	Urea Norway	Urea United Kingdom	Urea United States	Urea Saudi Arabia	UAN Norway	UAN United Kingdom	UAN United States	UAN Saudi Arabia
Total	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Climate change	%	10.95	11.37	11.57	0.06	6.99	10.12	10.21	0.04
Ozone depletion	%	2.06	0.93	0.71	0.00	0.97	0.80	0.61	0.00
Particulate matter	%	8.68	6.00	24.06	0.07	10.02	6.62	21.52	0.05
Ionizing radiation HH	%	9.43	37.57	11.30	0.02	4.51	31.95	9.66	0.01
Ionizing radiation E (interim)	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Photochemical ozone formation	%	12.94	7.53	6.28	0.05	12.21	7.97	6.43	0.04
Acidification	%	10.90	8.40	8.86	0.08	15.92	9.88	9.41	0.06
Terrestrial eutrophication	%	10.55	5.61	3.69	0.03	8.96	5.79	3.83	0.02
Freshwater eutrophication	%	1.37	2.00	6.07	0.00	1.33	1.87	5.29	0.00
Marine eutrophication	%	7.70	4.73	3.19	0.03	6.97	4.88	3.29	0.02
Land use	%	0.46	1.72	1.47	0.01	2.21	1.97	1.61	0.01
Water resource depletion	%	2.68	5.02	17.31	99.63	1.80	5.86	20.49	99.72
Mineral. fossil & ren resource depletion	%	22.28	9.13	5.49	0.02	28.11	12.29	7.65	0.02

3.8 Sensitivity analysis

In the industrial synthesis of ammonia, carbon dioxide (CO_2) is a by-product in the steam-methane-reforming (SMR) process which is mostly processed during the subsequent step of urea production. Although carbon dioxide has some marketability, as a product (carbonation of beverages, wastewater pH adjustment, etc.), it is relatively smaller by volume compared to the ammonia market. It also does not have an established global supply chain and market. In addition, carbon dioxide may also be associated with abatement or externality costs depending on the existence of regulations and/or carbon markets. Moreover, many ammonia production facilities also produce urea (EPA, 2009)[24]. In fact, urea production is the largest consumer of synthetic ammonia in the U.S. Fertilizer producers can send their ammonia directly to market or they can use it to produce urea.

Bearing this in mind, in this study the authors have assumed that ammonia is the key desired co-product for integrated urea-ammonia facilities. This implied that all environmental burdens of the process have been attributed to ammonia and none to carbon dioxide. However, in order to check how this assumption affects LCA results, a sensitivity analysis was carried out by applying an economic allocation approach, i.e. partitioning of the inputs/output of the process between the different co-products ammonia and CO_2 based on their current market values (ISO 14044, 2018)[25]. This could provide an additional incentive for the recovery of carbon dioxide as a useful co-product and its utilisation for the urea process or other emerging industrial applications.

As it can be observed in table 43, with respect to Case 1 and Case 2 (i.e. Urea and UAN 32.0.0 solution synthesis respectively from natural gas without and with CO_2 capture technology from SMR flue gases), around 62% of the total economic value of the products is allocated to ammonia, whilst 38% to CO_2. About Case 3 (i.e. Urea and UAN 32.0.0 solution synthesis from hybrid natural gas/water electrolysis with CO_2 capture technology), 68% of the total economic value of the products is allocated to ammonia, whilst 32% to CO_2.

Table 43. Economic allocation.

Product	**Amount (tonne)**	**Amount (tonne)**	**Amount (tonne)**	**Price (€/tonne)**	**Economic allocation (%)**	**Economic allocation (%)**	**Economic allocation (%)**
	Case 1	**Case 2**	**Case 3**		**Case 1**	**Case 2**	**Case 3**
Ammonia	2,000	2,000	2,000	186[a]	**62%**	**62%**	**68%**
CO_2 feedstock	2,510	2,510	1,888	92[b]	**38%**	**38%**	**32%**

[a] *Ammonia price was calculated as average of market prices (referred to 2020), in European, US and Middle East regions.*
[b] *Source: EU Eurostats Prodcom database. Available on: https://ec.europa.eu/eurostat/web/prodcom/data/database (accessed October 2020).*

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[24] EPA, 2009. Technical Support Document for the Ammonia Production Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases. Office of Air and Radiation, U.S. Environmental Protection Agency.

[25] ISO 14044:2006/A1:2018. Environmental management — Life cycle assessment — Requirements and guidelines

A comparison of LCA results with and without allocation procedure performed for all above investigated cases is showed in the following figures 27:29. Since the present study is focused on decarbonization in fertilizers' production, the sensitivity analysis has been performed on the two regions with the lower and higher impact on climate change (i.e. Norway and Saudi Arabia).

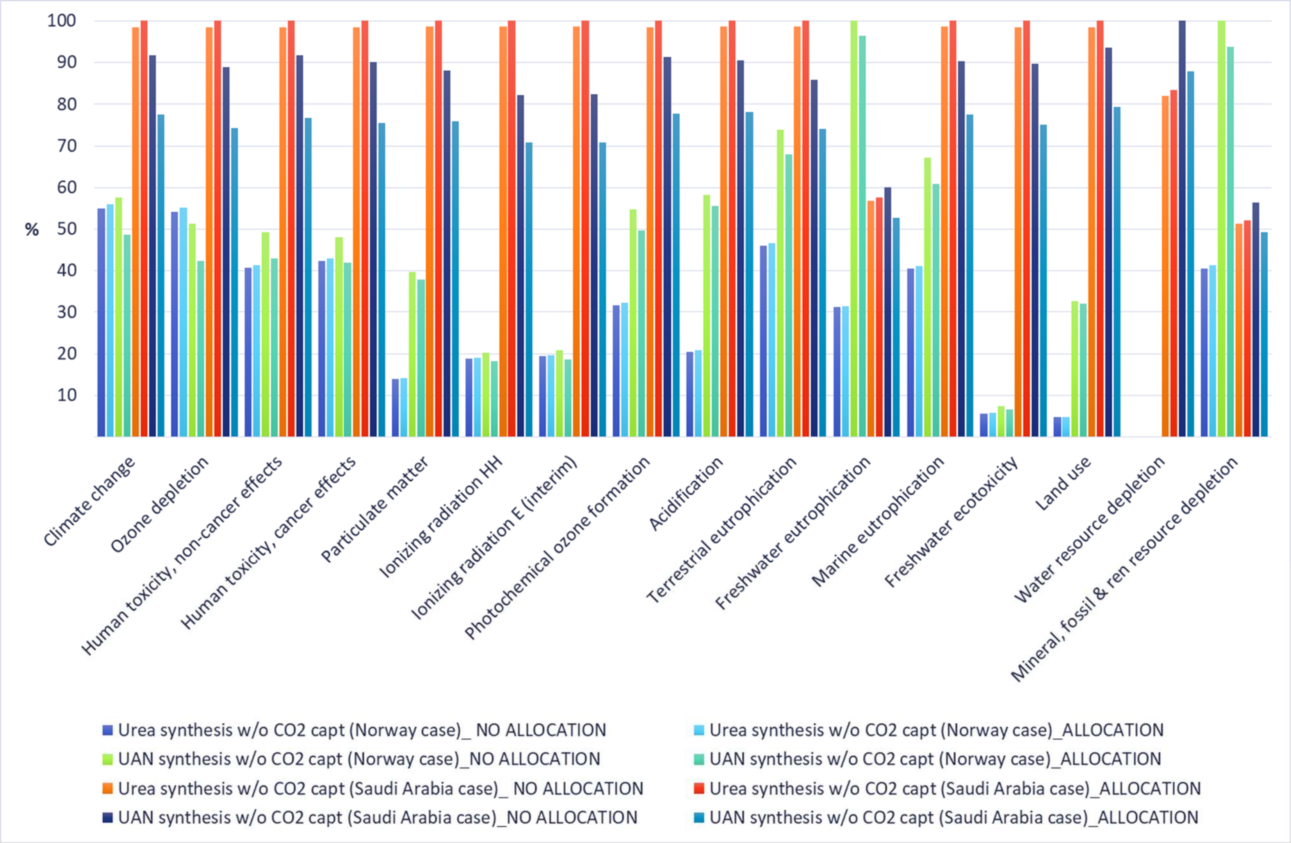

Figure 27. Case 1- comparison LCA results for Urea and UAN 32.0.0 solution synthesis (Norway and Saudi Arabia case) with and without economic allocation.

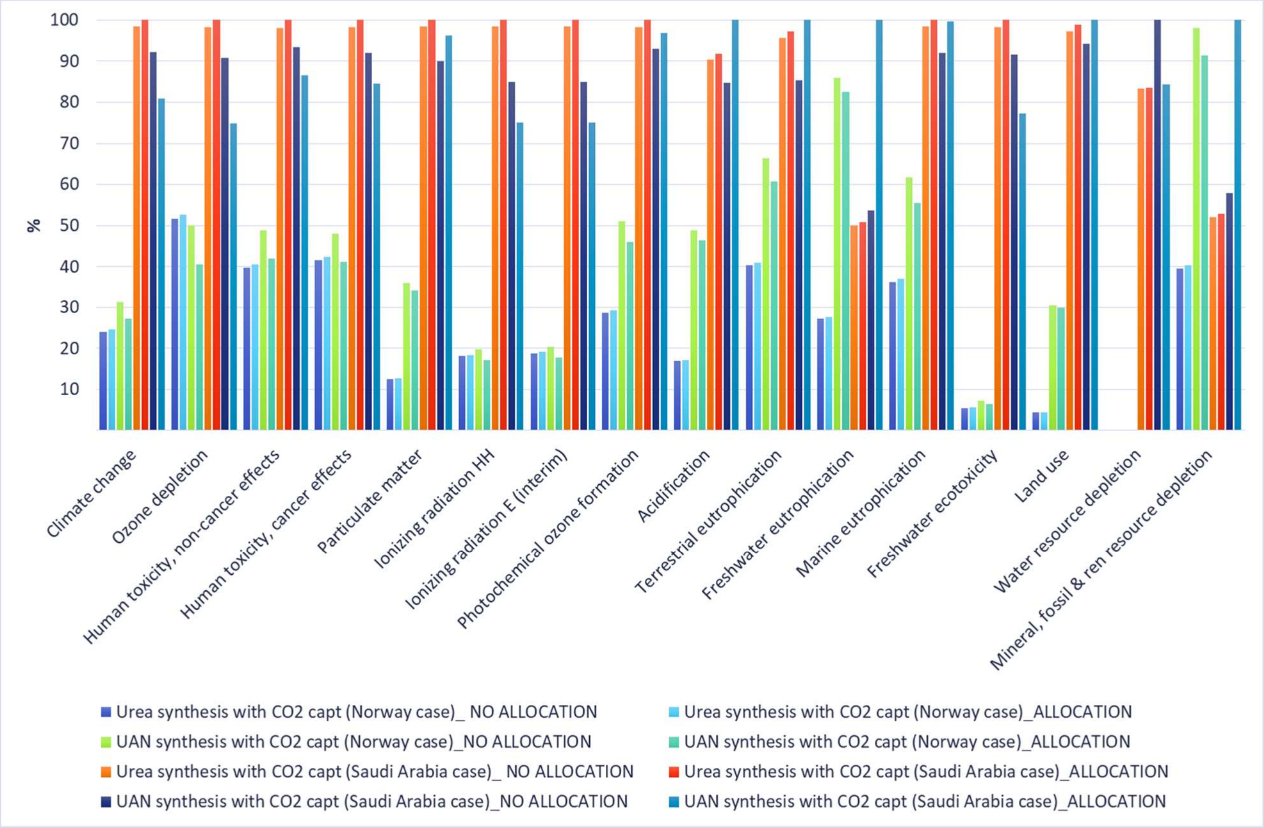

Figure 28. Case 2- comparison LCA results for Urea and UAN 32.0.0 solution synthesis (Norway and Saudi Arabia case) with and without economic allocation.

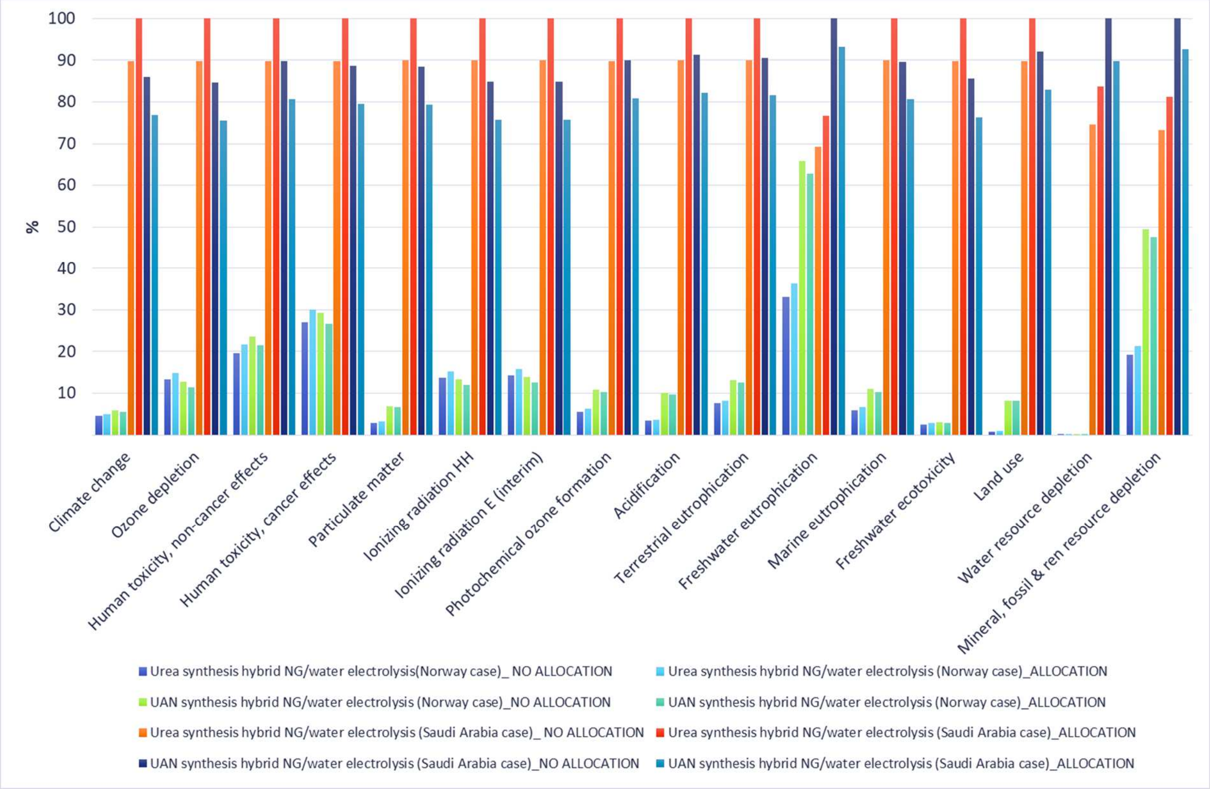

Figure 29. Case 3- comparison LCA results for Urea and UAN 32.0.0 solution synthesis (Norway and Saudi Arabia case) with and without economic allocation.

As illustrated in figure 27, in Case 1 (i.e. fertilizers' production from natural gas without CO_2 capture technology) applied to Norway and Saudi Arabia regions, the comparison of LCA results with and without economic allocation shows a difference of values across all impact categories up to a maximum of 2% as for Urea synthesis and 16% as for UAN solution synthesis. Looking at Case 2 depicted in figure 28, a difference of results with/without allocation across is observed in almost all impact categories up to a maximum of 2% as for Urea synthesis and 18% as for UAN solution synthesis (except for Saudi Arabia case, where freshwater eutrophication and mineral, fossil & renewable resource depletion categories have a variation of values up to 87%). In Case 3 (figure 29), the variation of results reaches a maximum of 12% and 11% across all impact categories, respectively for Urea synthesis and UAN solution synthesis.

3.9 Additional information

Urea fertilizer as a product is not an appropriate option for carbon sequestration. The hydrolysis of urea after its application as a fertilizer releases to the atmosphere nearly all CO_2 captured in the urea molecule. Therefore the release of CO_2 has to be considered in the inventory for the agricultural production.

The downstream processes of investigated fertilizers' production (i.e. distribution. use and end of life) are outside the scope of this analysis. However, the authors believed useful to put in this report the CO_2 emissions after the urea fertilizer application as an additional information for the stakeholders.

In line with Yara[26], around 98% of CO_2 is released in 8 days from urea fertilizer. Thus, according to this study, the **use of every tonne urea essentially induces 0.73 tonne CO_2 emission after its usage.**

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[26] Yara Research Center Hanninghof, 2016. CO_2 emission after Urea application. Available on: https://ammoniaindustry.com/wp-content/uploads/2016/04/CO2-emissions-during-urea-hydrolysis.pdf

5. TASK 4 – CONCLUSIONS AND OVERVIEW OF DIRECT APPLICATIONS (LCA)

Client : IEAGHG
Project Name : Feasibility Study on Achieving Deep Decarbonization in Worldwide Fertilizer Production
Document Name : Tasks 4 - Conclusions and overview of direct applications
AmecFWI contract : 1-BD-1160A

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Conclusions and overview of direct applications

Global carbon dioxide (CO_2) emissions have continued to rise significantly increasing the potential for climate change. Under the auspices of the UN Framework Convention on Climate Change and through the Paris Agreement, there is a commitment to keep global temperature increase to well below two degrees Celsius. This will require a variety of strategies including increased renewable power generation and broad scale electrification, increased energy efficiency, and carbon-negative technologies.
The agricultural sector also contributes to worldwide greenhouse gas (GHG) emissions with a share that is 10–12% of CO_2 equivalent[1]. Considering indirect emissions from other activities related to agriculture such as fertilizer production, land use change, food storage, packaging etc., this share can be up to one-third of the total GHG emissions[2]. It is acknowledged that fertilizers are basically produced from ammonia. It is estimated that ammonia production is responsible for about 420 million tonnes of CO_2 emissions, over 1% of global energy-related CO_2 emissions[3]. It then follows that the feedstock used in ammonia production will play a significant role in the amount of energy consumption and CO_2 emissions produced during food production. Ammonia is the precursor of nearly all mineral nitrogen fertilizers, such as ammonium nitrate and urea. In order to limit the impact on the environment caused by the current ammonia production routes, which rely greatly on fossil fuels both as an energy source and as feedstock, other greener and sustainable production pathways need to be implemented. Since only nitrogen and hydrogen are required for ammonia synthesis, there are few variables for process optimization. When considering the environmental impact of the ammonia production process from natural gas, it can be improved by making the raw materials supply chains more environmentally friendly. Nitrogen is mainly obtained from compressed air into the process, while hydrogen can be obtained from various resources, either renewable (e.g. water, biomass) or non-renewable (e.g. coal, natural gas, heavy fuel oil), through different technologies. Therefore, the hydrogen production route is the primary variable in the environmental impact of the ammonia process.

Life Cycle Assessment (LCA) is a useful tool to prove that a technology could contribute to the mitigation of environmental impacts. LCA is a methodology to account for the environmental impacts of a product or service throughout its entire life cycle. The present study used a Life Cycle Analysis (LCA) approach to investigate the environmental impact of Urea and Urea Ammonium Nitrate solution (UAN 32.0.0) fertilizers via three different production routes, focusing on the ammonia precursor synthesis process. Three ammonia production routes were evaluated, resulting in three cases. For comparison reasons, the conventional ammonia

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[1] Sonesson U., Davis J. and Ziegler F., 2009. Food Production and Emissions of Greenhouse Gases. An overview of the climate impact of different product groups. Institutet för livsmedel och bioteknik: Göteborg, Sweden, 2010; pp. 1–26 [Accessed February, 2021].

[2] Gilbert A., One-third of our greenhouse gas emissions come from agriculture, Farmers advised to abandon vulnerable crops in face of climate change, 2012, https://www. nature.com/news/one-third-of-our-greenhouse-gas-emissionscome- from-agriculture-1.11708 [Accessed February, 2021].

[3] Philibert C. Producing ammonia and fertilizers: new opportunities from renewables, 2017. https://www.ee.co.za/wp-content/uploads/2017/06/Producing-ammonia-and-fertilizers-new-opportunities-from-renewables.pdf [Accessed October, 2020].

production path (i.e. Haber-Bosch process with H_2 obtained from SMR –steam-methane-reforming and N_2 from compressed air to the secondary reformer) is used as base case (named Case 1), representing the state-of-the-art for ammonia synthesis. In Case 1, natural gas is used as feedstock for ammonia production and CO_2 emission from flue gas are released to the atmosphere. The CO_2 capture from SMR flue gases by means of CCS –capture and storage technology and its effect on the overall environmental impact of the final urea and UAN fertilizer synthesis was investigated in the Case 2. In addition, a hybrid production of ammonia from water electrolysis (partial) and natural gas, with CO_2 capture from SMR flue gases was evaluated in Case 3.
Furthermore, the aim of this study was to demonstrate how deep decarbonisation of fertilizers' production can be achieved for regions such as Europe, North America, and Middle East. Therefore, the sustainability performances in four different countries (United Kingdom–UK, Norway–NO, United States–US, Saudi Arabia–SA) that are representative of certain regional conditions were compared, in order to see how the electricity supplier affect the environmental profile of the investigated fertilizers.

From a Process standpoint, the plant configuration has been considered the same for all locations with exception of Middle East, in which, due to sweet water scarcity, a desalination section has been foreseen to make use of sea water.

Results of Task 1 showed that cold climates are beneficial for the performance of the plant, as compressions are carried out with higher efficiency, and more power can be extracted from condensing steam turbines.

A cradle-to-gate LCA was performed, adopting as functional units 1 tonne Urea and 1 tonne UAN 32.0.0. solution fertilizers and discussing sixteen environmental impact categories included in the ILCD method implemented in SimaPro software.

Overall, results obtained in Task 3 showed that for all investigated regions, the integration of CCS technology (i.e. Case 2) in the ammonia synthesis route (precursor for urea and UAN production) has a significant influence on the climate change indicator, showing a reduction of more 30% when compared to the conventional ammonia synthesis route (i.e. Case 1). This result was attributed to the decrease of direct CO_2 emissions from the ammonia process derived from CO_2 capture unit. Specifically, the highest environmental benefit in climate change category was gained for Norway case where an impact reduction up to 70% was observed. In UK, US and Saudi Arabia the impacts decreased by 53%, 40%, 33% respectively.
Although for Case 2 the climate change indicator has the lowest values amongst the investigated cases, the rest of the environmental impact categories do not follow the same trend. Case 2 (i.e. urea and UAN production with CCS technology) performs slightly worst (i.e. up to 15%) compared with conventional case (Case 1). In particular, for water resource depletion category the differences arise mainly from the additional plant consumptions to capture and sequestrate CO_2 increase for water resources depletion due to a higher sea/lake water consumption used to accomplish the inter-refrigeration cooling duty of CO_2 compressors.
In the case of hydrogen produced from hybrid natural gas/water electrolysis (i.e. Case 3) it results in the highest overall environmental impacts compared to Case 1 and Case 2, except for

water resource depletion category in UK, US and Saudi Arabia. In Norway case the results follow a different trend compared to the other countries. Case 3 in Norway, has the lowest impact on climate change, ozone depletion, photochemical ozone formation, acidification, marine eutrophication, land use and mineral, fossil and renewable depletion.

Furthermore, while in UK, US and Saudi Arabia water depletion is higher in Case 2 compared to Case 3, in Norway results are the opposite. The main contributor to water depletion indicator in UK, US and Saudi Arabia for Cases 2 and 3 is the cooling water. The amount of cooling water consumed in Norway is less than the other countries; moreover, what it significantly changes is the characterization factor that the impact assessment method gives to Norway water. Among the four analysed regions, Norway is the one less affected by water scarcity problems. For this reason, on the overall impact on water depletion, the higher water consumption of cooling water in Case 2 does not affect the results. The main contributor to Norway water depletion impact category is given by the electricity and, in particular, by the water consumed in electricity production processes. Case 3 uses more electricity compared to Case 2 and this explains its higher impact of water depletion impact category.

In general the results implied that the environmental burdens of investigated fertilizers' production are mainly affected by energy (natural gas and electricity) demand and supply chain. Norway case was found to be the most sustainable option for fertilizers' synthesis due to its significant environmental savings compared to other cases. This finding is explained by the fact that according to IEA statistics the share of renewables in Norway electricity mix (in particular hydropower) is higher than 90%; conversely, in the rest of analysed regions the share of renewables in the electricity mix is lower, approximately 25% (United Kingdom), 17% (United States), 1% (Saudi Arabia).

This study suggests that by transitioning to renewable electricity sources, such as hydro, biomass, geothermal, solar and wind for power generation, and implementing a more sustainable production alternative, instead of the conventional Steam Reforming technology, for ammonia production, the overall environmental burden of the nitrogen fertilizers can be reduced. Thus, areas with abundant hydropower resources such as Norway and others are possible choices for siting CCS technologies or electrolysers.

Since the environmental impacts from fertilizers' production are closely associated with energy consumption, the two investigated regions with highest and lowest share of renewables in the electricity mix production (respectively from 90% of Norway to 1% of Saudi Arabia) were selected in order to summarize the final results and considerations of this report. The LCA results for Norway and Saudi Arabia are presented in figures 1:3.

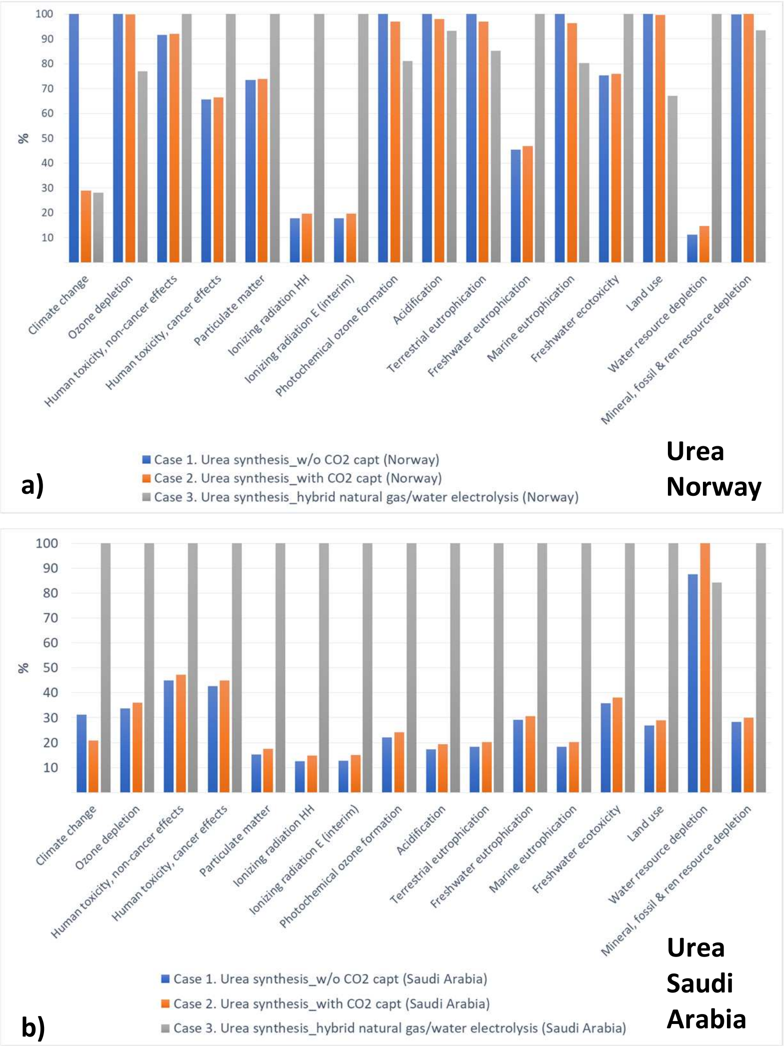

Figure 1. a) Environmental profile of urea production in Norway via three different production routes b) Environmental profile of urea production in Saudi Arabia via three different production routes.

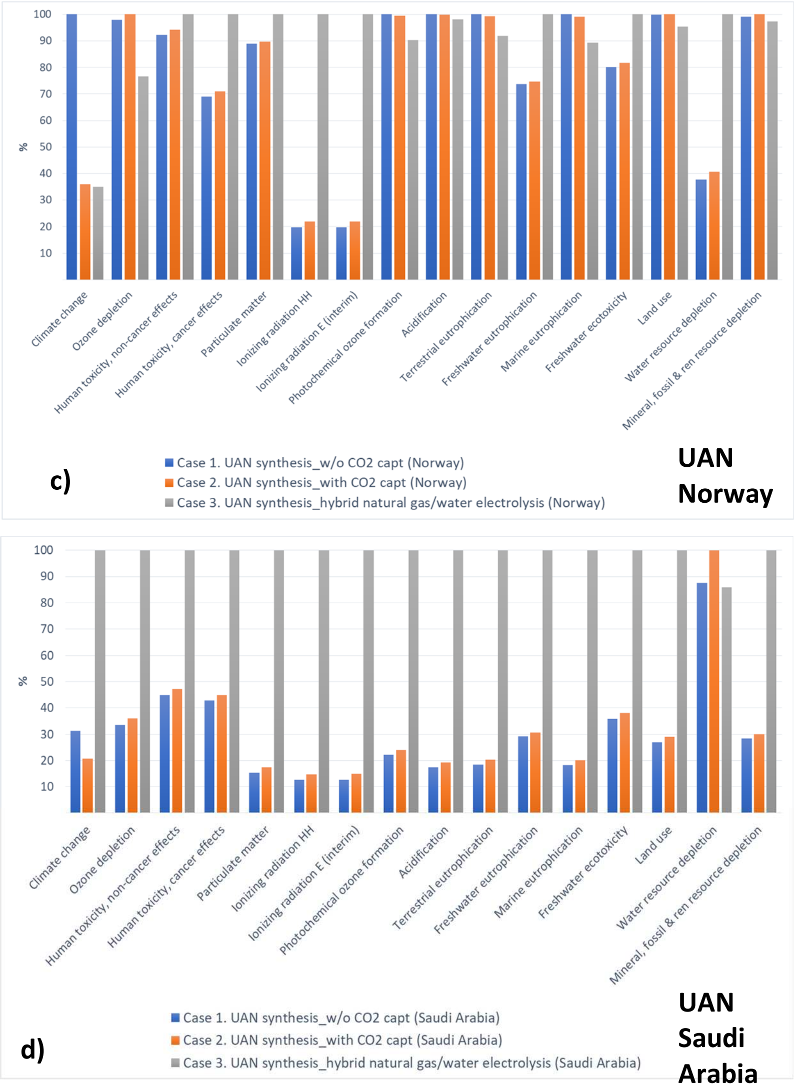

Figure 2. c) Environmental profile of UAN 32.0.0 production in Norway via three different production routes d) Environmental profile of UAN 32.0.0 production in Saudi Arabia via three different production routes.

Figure 3. Environmental profile of Urea production in Norway and Saudi Arabia regions.

Especially the emissions of greenhouse gases play an important role in the fertilizer supply chain. The production of Urea and UAN fertilizers causes greenhouse gases in a large extent (mainly CO_2) due to the use of electricity and fossil fuels in the ammonia production and in a lesser extent due to nitrous oxides. Therefore, the present report focused on direct/indirect CO_2 emissions and climate change as the most important environmental impact category. Table 1 below summarizes the LCA results for Norway and Saudi Arabia, which represent the countries with highest/lowest proportion of renewable energy resources.

Table 1. LCA results for climate change category.

Product	Country	Unit	Case 1, base case (natural gas without CO_2 capture)	Case 2 (natural gas with CO_2 capture)	Case 3 (hybrid natural gas/water electrolysis with CO_2 capture)
Urea	Norway	kg CO_2 eq/tonne	383	111	108
Urea	Saudi Arabia	kg CO_2 eq/tonne	686	453	2,138
UAN 32.0.0	Norway	kg CO_2 eq/tonne	402	144	140
UAN 32.0.0	Saudi Arabia	kg CO_2 eq/tonne	639	424	2,045

Recommendation

For futures studies, it is recommended to evaluate the following case scenarios:

- Evaluate, from environmental, economic perspectives and societal performances such as employment and safety, cases for ammonia production where hydrogen production is entirely obtained from electrolysis route using non-fossil sources. This could make the solution either close to 100% zero carbon or carbon negative if the CO_2 emissions from agricultural use of the urea fertiliser are discounted.

- In the long term, CO_2 recycling can become a key element of sustainable carbon - resource management in chemical and energy companies, combined with curbing consumption. For a better and more complete picture, scenario studies of different CO_2 utilization systems[4] (e.g. for enhanced oil recovery (EOR), polymers, CH_4, methanol) covering more than just climate impact should be performed.

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[4] M. Voldsund, K. Jordal and R. Anantharaman, 2016. Hydrogen production with CO_2 capture, Int. J. Hydrogen Energy, 41(9), 4969–4992.

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