

DECARBONISATION OPTIONS FOR THE DUTCH FERTILISER INDUSTRY

M. Batool, W. Wetzels

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Decarbonisation options for the Dutch fertiliser industry

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Authors

M. Batool and W. Wetzels

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FINDINGS

Summary

This report describes the current situation for fertiliser production in the Netherlands and the options and preconditions for its decarbonisation.

Fertilisers essentially provide three major nutrients (nitrogen, phosphorus and potassium) in plant crop available forms. This report focuses on the nitrogen-based fertiliser production at Yara Sluiskil and OCI Nitrogen, because these are the largest companies in terms of production volumes and energy consumption.

Yara Sluiskil produces around 5 million tonnes of fertiliser products per year. The production site has three ammonia plants, four CO₂ plants, two nitric acid plants, one urea prilling plant, one urea granulation plant and two nitrate granulation plants. The three ammonia plants ('C', 'D' and 'E') have a combined production capacity of approximately 1.8 million tonnes of NH₃ per year. Table S1 shows the estimated natural gas consumption and greenhouse gas emissions of ammonia, urea and nitric acid production at Yara Sluiskil B.V. in 2017.

Table S1 Estimated natural gas consumption and greenhouse gas emissions of ammonia, urea and nitric acid production at Yara Sluiskil B.V. in 2017

	Ammonia plant C	Ammonia plant D	Ammonia plant E	Urea	Nitric acid	Total
Capacity [kt of product/year]	449	639	731	1,300	1,500	-
Production [kt of product/year]	410	584	668	1,187	1,370	-
Input of natural gas [PJ]	14.0	19.9	22.4	0.0	0.0	56
Greenhouse gas emission [MtCO ₂ eq]	0.8	1.1	1.3	0.0	0.2	3.4

OCI Nitrogen B.V. in Geleen is a large producer of fertilisers and the world's largest producer of melamine. OCI Nitrogen operates production plants for ammonia, nitric acid, ammonium nitrate, urea, Urea Ammonium Nitrate (UAN), Calcium Ammonium Nitrate (CAN) and melamine. The two ammonia plants ('AFA-2' and 'AFA-3') have a combined production capacity of approximately 1.2 million tonnes of NH₃ per year. Table S2 shows the estimated natural gas consumption and greenhouse gas emissions of ammonia, urea and nitric acid production at OCI Nitrogen B.V. in 2017.

Table S2 Estimated natural gas consumption and greenhouse gas emissions of ammonia, urea and nitric acid production at OCI Nitrogen B.V. in 2017

	Ammonia (AFA-2 and AFA-3)	Urea	Nitric acid	Total
Capacity [kt of product/year]	1,184	525	965	-
Production [kt of product/year]	1,081	479	881	-
Input of natural gas [PJ]	38.1	0.0	0.0	38.1
Greenhouse gas emission [MtCO ₂ eq]	2.2	0.0	0.1	2.3

Ammonia production is the most energy-intensive process in the fertiliser industry. In the conventional ammonia production process, ammonia is produced by steam methane reforming of natural gas combined with Haber-Bosch NH₃ synthesis. Alternatively, hydrogen with a lower CO₂ footprint (e.g. green hydrogen) can be produced on-site or supplied from external sources. Ammonia plants produce large flows of almost pure CO₂ gas, which are potentially well suited for carbon storage (CCS).

FULL RESULTS

Introduction

This report describes the current situation for fertiliser production in the Netherlands and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts and the energy sector in their common efforts to achieve deep decarbonisation. Mapping decarbonisation options is an ongoing process. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Scope

Production locations:

- Yara Sluiskil B.V.
- OCI Nitrogen B.V.

Processes:

- Production of ammonia from natural gas;
- Production of urea from ammonia and carbon dioxide;
- Production of nitric acid from ammonia.

Products of the fertiliser industry include:

- Ammonia;
- Nitric acid;
- Ammonium Nitrate (AN);
- Calcium ammonium nitrate (CAN);
- Urea;
- Urea Ammonium Nitrate (UAN);
- Compound fertilisers.

Main decarbonisation options are using hydrogen with a lower CO₂ footprint (e.g. green hydrogen from electrolysis) and carbon capture and storage.

Reading guide

Section 1 introduces the Dutch fertiliser industry. Section 2 describes the current situation for fertiliser production processes in the Netherlands and Section 3 discusses the products that are produced in these processes. Options for decarbonisation are examined in Section 4. The feasibility of these decarbonisation options is discussed in Section 5.

1 Fertiliser production in the Netherlands

This chapter discusses the fertiliser industry of the Netherlands. Detailed information is presented on Yara Sluiskil B.V. and OCI Nitrogen B.V.

1.1 The Dutch fertiliser industry

The Dutch fertiliser industry employs approximately 2,000 people. In 2016, the total operating income was EUR 2.1 billion and the profit before taxation was EUR 0.2 billion. The costs of raw materials and consumables (EUR 0.6 billion) and the costs of energy (EUR 0.2 billion) represent a substantial share of the total operating expenses (see Table 1) (CBS, 2018).

According to the NACE classification, the activities of the fertiliser sector include (Eurostat, 2008):

- manufacture of fertilisers:
 - straight or complex nitrogenous, phosphatic or potassic fertilisers;
 - urea, crude natural phosphates and crude natural potassium salts;
- manufacture of associated nitrogen products:¹
 - nitric and sulfonitric acids, ammonia, ammonium chloride, ammonium carbonate, nitrites and nitrates of potassium.

In the Netherlands, the four main fertiliser producing companies are Yara Sluiskil B.V., OCI Nitrogen B.V., ICL Fertilisers and Rosier Nederland (Meststoffen Nederland, 2015). This report focuses on the nitrogen-based fertiliser production at Yara Sluiskil and OCI Nitrogen, because these are the largest companies in terms of production volume and energy consumption.

Rosier Nederland B.V. annually produces approximately 500,000 tonnes of fertilisers with nitrogen, phosphate, potassium and sulfur as main components (Rosier Nederland B.V., 2019). In 2017, EU ETS emissions from Rosier Nederland B.V. were 16,245 tCO₂eq. ICL Amsterdam produces approximately 600,000 tonnes of (mainly phosphate potassium) fertilisers per year (ICL, 2019). In total, the fertiliser industry in the Netherlands comprises 40 companies².

¹ Ammonium chloride and ammonium carbonate are not produced in the Netherlands.

² CBS data for the first quarter of 2018 from the statistic 'Bedrijven; bedrijfstak' [businesses: business sector].

Table 1 Labour data and financial data for the Dutch fertiliser industry, for 2009–2017. Source: (CBS, 2018)

Fertiliser industry (SBI 20.15)	Unit	2009	2010	2011	2012	2013	2014	2015	2016	2017
Jobs (employees)	x 1,000	1.4	1.4	1.4	1.3	1.7	1.9	1.8	1.8	1.9
Jobs (employed persons)	x 1,000	1.6	1.5	1.6	1.4	1.9	2.0	2.0	2.0	2.1
Labour volume (employees)	x 1,000	1.4	1.3	1.4	1.2	1.7	1.8	1.7	1.7	1.8
Labour volume (employed persons)	x 1,000	1.5	1.5	1.5	1.4	1.8	1.9	1.9	1.9	1.9
Operating income (total)	x EUR million	1,306	2,254	2,581	2,062	2,948	2,720	2,613	2,117	2,165
Operating expenses (total)	x EUR million	1,310	1,988	2,188	1,750	2,678	2,366	2,190	1,891	1,947
Costs of sales (total)	x EUR million	755	1,356	1,461	1,259	1,752	1,448	1,351	1,070	1,147
of which: raw materials and consumables	x EUR million	637	966	1,114	850	972	825	861	581	657
of which: trade goods	x EUR million	116	281	258	403	775	615	489	488	488
Personnel expenses	x EUR million	140	152	174	112	159	176	173	208	181
Other operating expenses (total)	x EUR million	357	401	460	304	647	615	542	483	494
of which: energy costs	x EUR million	160	169	194	134	287	222	197	165	194
Depreciation on fixed assets	x EUR million	57	79	93	74	121	127	124	130	126
Operating result	x EUR million	-3	267	393	313	270	355	423	226	218
Profit before taxation	x EUR million	-11	283	463	295	262	372	440	207	205

Natural gas is the main input for the nitrogen fertiliser industry. In 2017, the total consumption of natural gas was 96.3 PJ (3.04 billion Nm³).³ Most of the natural gas can be attributed to non-energy consumption (69.6 PJ). The non-energy use of natural gas in the fertiliser industry can be fully allocated to ammonia production (Neelis, 2008). The final consumption of electricity was 2.7 PJ (0.75 TWh).⁴ The net electricity supply from the grid was 1.8 PJ (0.50 TWh). Natural gas is also used as an input for combined heat and power (CHP) installations, which produce electricity and heat. Figure 1 shows the development of the final energy and non-energy consumption of the Dutch fertiliser industry for the period 2013–2017. Table 2 shows the full energy balance for the sector in the same period.

³ Based on a Net Calorific Value of 31.65 MJ/Nm³.

⁴ 1 TWh = 3.6 PJ.

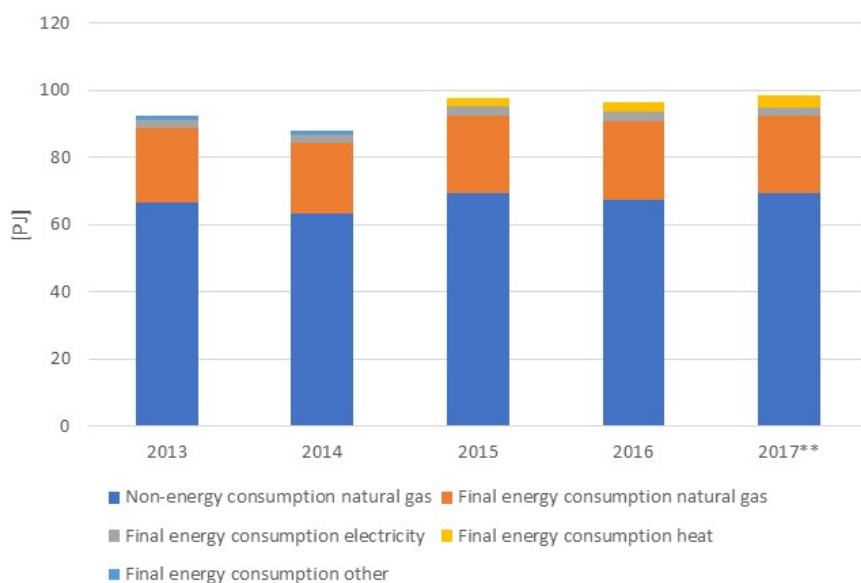


Figure 1 Final energy and non-energy consumption of the fertiliser industry of the Netherlands in 2013–2017. Source: CBS⁵

Table 2 Energy balance for the fertiliser industry of the Netherlands. Source: CBS⁶

[PJ]	Energy carrier	2013	2014	2015	2016	2017*
Final energy consumption	Natural gas	22.4	21.2	23.2	23.3	22.7
	Waste and other energy sources	1	1.1			
	Electricity	2.5	2.5	2.6	2.7	2.7
	Heat	0	0	2.6	3.0	3.4
Non-energy consumption	Natural gas	66.5	63.2	69.4	67.5	69.6
Net consumption electricity/CHP transformation	Natural gas	4.0	4.1	4.0	3.8	3.9
	Electricity	-0.9	-0.9	-0.9	-0.8	-0.9
	Heat	0	0	-1.5	-2	-2.3
Net consumption other transformations	Waste and other energy sources	1.8	1.4	2.1	1.7	2.8
	Heat	-1.8	-1.4	-2.1	-1.7	-2.8
Total consumption	Natural gas	93	88.5	96.5	94.7	96.3
	Waste and other energy sources	2.8	2.5	2.1	1.7	2.8
	Electricity	1.5	1.6	1.7	1.8	1.8
	Heat	-1.8	-1.4	-1.1	-0.7	-1.7
Energy supply (+)	Natural gas	93	88.5	96.5	94.7	96.3
	Electricity	1.5	1.6	1.7	1.9	1.8
	Heat	1.1	1.2	1.1	1.1	1.2
Energy delivery (-)	Heat	3.0	2.6	2.3	1.8	2.9
Winning	Waste and other energy sources	2.8	2.5	2.1	1.7	2.8

⁵ Sector 2015 'Manufacture of fertilisers and nitrogen compounds'. Data for 2017 are revised provisional (CBS, 2018).

⁶ Data for 2017 are revised provisional.

1.2 Yara Sluiskil B.V.

Yara Sluiskil produces around 5 million tonnes of fertiliser products per year (Yara Sluiskil B.V., 2017). The production site, which is located at the canal from Gent to Terneuzen, was opened in 1929 (Yara, 2018a). The site was formerly known as Hydro Agri Sluiskil B.V. Now, it is a production site of the Norwegian company Yara International ASA (Yara, 2019). In 2017, Yara Sluiskil had 594 employees (Yara Sluiskil B.V. , 2018).

Yara Sluiskil has three ammonia plants, four CO₂ plants, two nitric acid plants, one urea prilling plant, one urea granulation plant and two nitrate granulation plants (Yara, 2018b). The three ammonia plants ('C', 'D' and 'E') use natural gas to produce ammonia and have a combined production capacity of approximately 1.8 million tonnes of NH₃ per year.

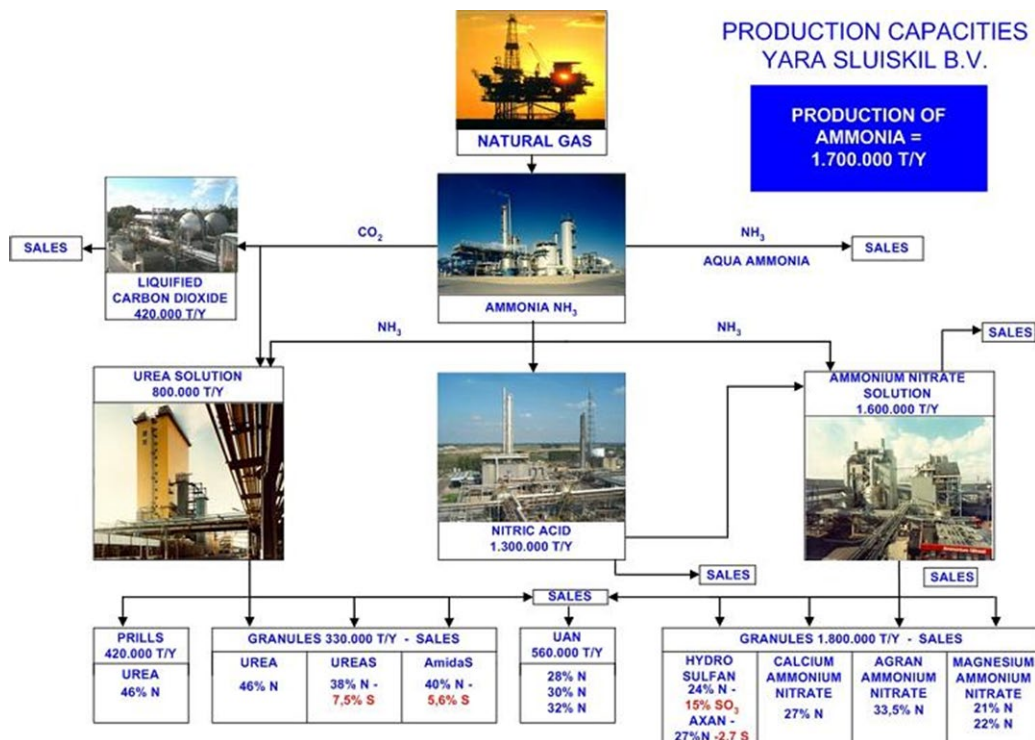


Figure 2 Production capacities of Yara Sluiskil B.V. in 2007 (Verkerke, 2007)

Figure 2 shows the production capacities of Yara Sluiskil in 2007. There have been several changes to the site since then. Some of the main changes are:

- In 2007, Yara replaced the gas turbine in its power station (Yara Sluiskil B.V., 2014).
- In 2009, Yara received a permit for a distribution system that delivers heat and CO₂ to greenhouse companies in the greenhouse area Kanaalzone in Terneuzen (Gedeputeerde Staten van Zeeland, 2009a). This 'WarmCO₂' project is an initiative of Yara Sluiskil and Zeeland Seaports. In 2017, heat and CO₂ were supplied to 96 out of a potential 150 hectares (Yara Sluiskil B.V., 2017). The greenhouses are supplied with water at 85 °C (Yara Sluiskil B.V. , 2018).
- In 2017, Yara received a permit to add a 'shell and tube' heat exchanger at ammonia plant E. The heat exchanger heats water for the WarmCO₂ grid and allows to supply an additional 7 MW of heat to the greenhouse area (Gedeputeerde Staten van Zeeland, 2017a).

- Yara has increased its production capacity for urea solution. The 'Ureum 7' plant, which has a capacity of 1.3 million tonnes per year (Chemicals Technology, 2019), has replaced the 'Ureum 5' and 'Ureum 6' urea solution plants (Gedepueteerde Staten van Zeeland, 2015). The 'Ureum 7' plant was put into service in 2011 and required an investment of EUR 420 million (Yara Sluiskil B.V., 2014).
- Yara has replaced a steam turbine in its nitric acid plant with a new steam turbine that has a higher efficiency. This enabled an increased steam export (Yara Sluiskil B.V., 2014)⁷.
- The output of 'Ureum 7' (urea solution) is processed into solid end products (Gedepueteerde Staten van Zeeland, 2016). In March 2016, Yara started construction of a new urea granulation plant ('Ureum 8') (Yara Sluiskil B.V., 2017), replacing the 'Ureum 6' prilling plant. From 1 January 2018, the prilling tower has no longer been used and the urea solution is now being processed in the new granulator (Gedepueteerde Staten van Zeeland, 2017b). The granulation plant has a capacity of 660,000 tonnes per year and its construction required an investment of EUR 240 million (Petrochem, 2019)⁸.
- In March 2018, Yara has received an environmental permit to build and take into production a hydrogen receiving station. The hydrogen will be used in ammonia plant D (Gedepueteerde Staten van Zeeland, 2018).

Table 3 provides an overview of the estimated production capacity of Yara Sluiskil in 2017.

⁷ In 2003, Yara built a new steam turbine to replace three older turbines. The older turbines were taken out of operation (Gedepueteerde Staten van Zeeland, 2003).

⁸ 'Ureum 6' had a capacity of 1,400 t/day. The 'Ureum 8' granulator has a production capacity of 1,850 t/day of urea granules or 2,400 t/day of Amidas/Ureas granules. The energy consumption of 'Ureum 8' is higher than of 'Ureum 6', which is inherent to the process (Gedepueteerde Staten van Zeeland, 2016).

Table 3 Estimated production capacities of Yara Sluiskil B.V. in 2017

	Estimated production capacity [kt/year]	Source	Comments
Ammonia plant C (1973)	449	(Lako, 2009)	The daily production capacity of 1,231 tonnes NH ₃ has been multiplied by 365 days/year.
Ammonia plant D (1984)	639	(Lako, 2009)	The daily production capacity is 1,750 tonnes NH ₃ .
Ammonia plant E (1988)	731	(Lako, 2009)	The daily production capacity is 2,004 tonnes NH ₃ .
Ammonia total (C+D+E)	1,820		
Urea granules	660	(Petrochem, 2019)	
Nitrate granules	1,800	(Yara Sluiskil, 2011)	An old granulator in the nitrate granulation plant has been replaced by a new one (Yara Sluiskil B.V., 2014).
Urea prills	420	(Verkerke, 2007)	From January 1 2018, the prilling tower is no longer used and the urea solution is processed in a new granulator (Gedeputeerde Staten van Zeeland, 2017b).
Urea Ammonium Nitrate (UAN)	913	(Gedeputeerde Staten van Zeeland, 2010)	In 2010, Yara received a permit to expand the capacity of the UAN installation from 2300 t/day to 2500 t/day (Gedeputeerde Staten van Zeeland, 2010).
Ammonium nitrate	1,600	(Verkerke, 2007)	
Nitric acid	1,500	(Yara Sluiskil, 2011)	Yara produces nitric acid in 'Salpeterzuurfabriek 6' and 'Salpeterzuurfabriek 7' (Gedeputeerde Staten van Zeeland, 2000).
Urea	1,300	(Petrochem, 2019)	
Liquid CO₂	420	(Gedeputeerde Staten van Zeeland, 1998)	In 1998, Yara acquired a permit to expand the production of pure CO ₂ by building a fourth CO ₂ installation. The capacity increased from 300,000 t/year to 420,000 t/year (Gedeputeerde Staten van Zeeland, 1998).



Figure 3 The Yara Sluiskil site. Source: (Yara, 2018b)

Table 4 shows the EU ETS emissions of Yara Sluiskil B.V. in the period 2013–2018. In 2017, emissions amounted to 3.8 million tonnes CO₂eq. The EU ETS covers nitrous oxide (N₂O) emissions from the production of nitric acid (European Commission, 2016). The EU ETS not only covers the direct emissions, but also the CO₂ that is captured in the urea (to be released in the chain at a later moment) or CO₂ that is sold for other purposes (De Bruyn, Koopman, Van Lieshout, Croezen and Smit, 2014).

Table 5 shows CO₂ and N₂O emissions at Yara Sluiskil B.V. from the Dutch Pollutant Release and Transfer Register. In 2017, Yara emitted 3.6 million tonnes of CO₂ and 820 tonnes of N₂O. In its sustainability report, Yara reports figures that do not include the amount of CO₂ for carbon capture and utilisation.⁹ Investments in catalyst technologies have strongly reduced the amount of emitted N₂O (see Figure 4).

Table 4 EU ETS emissions of Yara Sluiskil B.V. in kt CO₂eq per year, for the 2013–2017 period. Source: Dutch Emissions Authority (NEa)

Plant	Permit	Annex I activity EU ETS	2013	2014	2015	2016	2017	2018
Yara Sluiskil B.V. BKG 1	NL-200400026	Production of ammonia	699	713	773	731	813	793
Yara Sluiskil B.V. BKG 2	NL-200400026a	Production of ammonia	1,186	1,031	1,234	1,240	1,236	1,221
Yara Sluiskil B.V. BKG 3	NL-200400026b	Production of ammonia	1,225	1,214	1,312	1,301	1,311	1,128
Yara Sluiskil B.V. BKG 4	NL-200400026c	Production of nitric acid	63	78	78	70	72	80
Yara Sluiskil B.V. BKG 5	NL-200400026d	Production of nitric acid	140	155	142	161	174	173
Yara Sluiskil B.V. BKG 6	NL-200400026e	Combustion plant	228	223	224	227	222	211
TOTAL			3,540	3,413	3,762	3,729	3,828	3,607

Table 5 Emissions of CO₂ and N₂O by Yara Sluiskil B.V. Source: Pollutant Release and Transfer Register (PRTR) ¹⁰

	Carbon dioxide [kt CO ₂ /yr]	Nitrous oxide [kt N ₂ O/yr]	Nitrous oxide [kt CO ₂ eq/yr]	Total [kt CO ₂ eq/yr]
2005	2,549	10.2	3,028	5,577
2010	2,641	0.79	235	2,876
2015	3,547	0.74	220	3,767
2016	3,501	0.78	231	3,732
2017	3,585	0.82	245	3,830

⁹ According to Yara, the amount of CO₂ for carbon capture and utilization was 1.4 Mt CO₂ in 2017 (Yara Sluiskil B.V. , 2018).

¹⁰ The CO₂ equivalent emissions have been calculated based on a Global Warming Potential (GWP) of N₂O of 298 tCO₂/tN₂O. There are minor differences compared to the ETS emissions in Table 4 which are likely due to rounding.

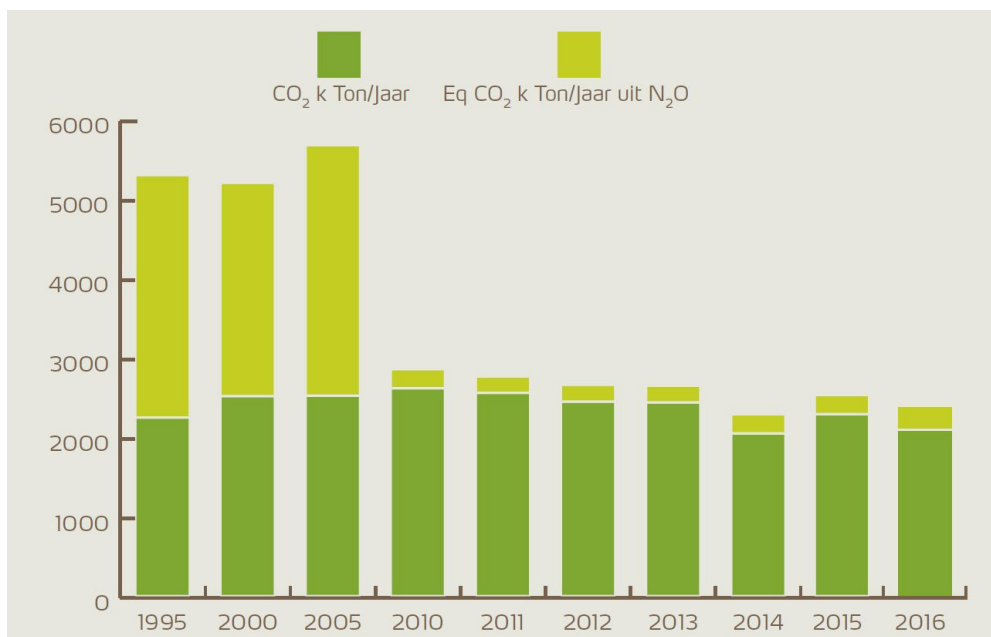


Figure 4 Greenhouse gas emissions from Yara Sluiskil’s sustainability report (Yara Sluiskil B.V., 2017)

1.3 OCI Nitrogen B.V.

OCI Nitrogen B.V. in Geleen is a large producer of fertilisers and the world’s largest producer of melamine (OCI Nitrogen, 2018a). In 1927, the company ‘Stikstofbindingsbedrijf’ (which was founded by the Dutch State Mines) commenced the construction of a fertiliser plant in Geleen. After several organisational changes, OCI Nitrogen was formed in a merger of DSM Agro and DSM Melamine in 2010 (OCI Nitrogen, 2018b). OCI Nitrogen is a subsidiary of OCI N.V., a global producer and distributor of natural-gas-based fertilisers and industrial chemicals (OCI N.V., 2018a).

Each year, OCI Nitrogen produces around 1 million tonnes of ammonia, of which approximately 900 kt are consumed by the Chemelot site users. About 100,000 tonnes of ammonia are sold and transported by rail. and about 6,000 tonnes by truck (OCI Nitrogen, 2018c).

The main office and the main production facilities are located on the Chemelot site in Geleen. OCI Nitrogen owns two port facilities: OCI Terminal Europoort and OCI Terminal Stein (OCI Nitrogen, 2018a). In the region of Limburg, OCI Nitrogen has approximately 500 employees (OCI Nitrogen, 2018a). In 2016, the turnover of OCI Nitrogen was approximately EUR 750 million (OCI Nitrogen, 2018d).

Figure 5 gives an overview of the production of mineral fertilisers at OCI Nitrogen. OCI Nitrogen operates production plants for ammonia, nitric acid, ammonium nitrate, urea, Urea Ammonium Nitrate (UAN) and Calcium Ammonium Nitrate (CAN). It also produces melamine, which is mainly used in the wood processing industry and for producing tableware, flame retardants and glues (Gedeputeerde Staten van Limburg, 2018a). Utility Support Group BV supplies energy and utilities to the Chemelot site (Gedeputeerde Staten van Limburg, 2017).

Table 6 shows OCI Nitrogen’s production capacities in 2017. Changes that have taken place at the site include:

- One of the nitric acid plants of DSM in IJmuiden was relocated to Geleen in 2010 (OCI Nitrogen, 2018b). In 2009, DSM Geleen had two nitric acid plants with capacities of 500 kt/year and 210 kt/year. The capacities of the DSM plants in IJmuiden were 245 kt/year and 255 t/year (Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut, 2009).
- In 2016, OCI Nitrogen invested in a catalyst replacement at its nitric acid plant to reduce its nitrous oxide emissions. According to OCI, this resulted in a 75% decrease in emissions (OCI N.V., 2018a).

Table 6 Estimated production capacities of OCI Nitrogen in the Netherlands in 2017

	Estimated production capacity [kt/year]	Source	Comments
Ammonia total (AFA-2 and AFA-3)¹¹	1,184	(OCI N.V., 2018a)	In 2009, ECN reported a capacity of 1,500 t/day for AFA-2 (built in 1971) and 1,500 t/day for AFA-3 (built in 1983) (Lako, 2009). 3,000 t/day corresponds to 1,095 kt NH ₃ /year (multiplied by 365 days/year).
Urea Ammonium Nitrate (UAN)	730	(OCI N.V., 2018a)	Full UAN capacity cannot be achieved when producing max. CAN capacity.
Nitric acid	965	(Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut, 2009)	One of the nitric acid plants of DSM in IJmuiden was relocated to Geleen (OCI Nitrogen, 2018b).
Urea	525	(European Commission, 2007)	
Calcium Ammonium Nitrate (CAN)	1,542	(OCI N.V., 2018a)	
Melamine	164	(OCI N.V., 2018a)	OCI Nitrogen's melamine production capacity of 55 ktpa in China is not included.

¹¹ This is the gross production capacity for ammonia. The estimated remaining capacity after downstream products are produced is 350 kt/year (OCI N.V., 2018a).

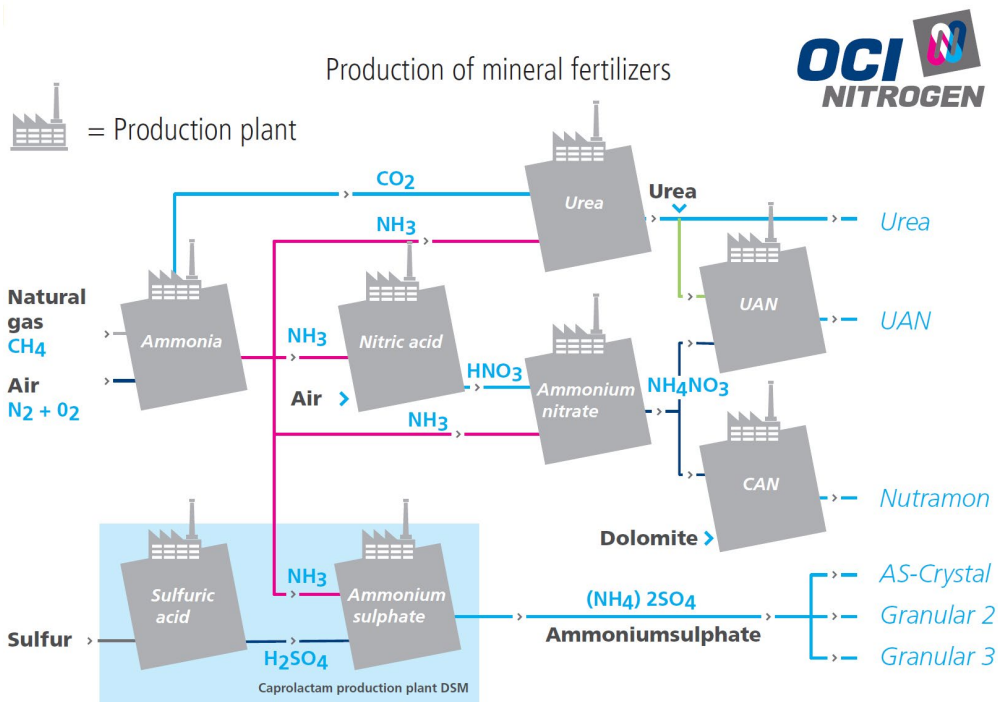


Figure 5 Overview of the production of mineral fertilisers at OCI Nitrogen B.V.
Source: (OCI Nitrogen., 2012)

Table 7 shows the ETS emissions of Chemelot in the period 2013–2018. In 2017, the EU ETS emissions of the Chemelot site were 4.7 million tonnes CO₂eq. Production of ammonia and nitric acid takes place in the plants Chemelot BKG 03-07, with combined emissions of 1.9 million tonnes CO₂eq in 2017.

Table 8 shows Chemelot's emissions of CO₂ and N₂O from the Pollutant Release and Transfer Register (PRTR). In 2017 Chemelot emitted 4.7 million t/CO₂ and the N₂O emissions were 4,170 t/N₂O.

Table 7 ETS emissions of Chemelot in kt CO₂eq. Source: Dutch Emissions Authority (NEa)

Plant	Permit	Annex I activity EU ETS	2013	2014	2015	2016	2017	2018
Chemelot BKG 01	NL-200400161	Combustion plant	747	769	757	731	595	754
Chemelot BKG 02	NL-200400161a	Production of organic bulk chemicals	1,517	1,755	1,695	1,788	1,772	1602
Chemelot BKG 03	NL-200400161b	Production of ammonia	950	857	945	920	1,014	759
Chemelot BKG 04	NL-200400161c	Production of ammonia	925	921	707	825	807	946
Chemelot BKG 05	NL-200400161d	Production of nitric acid	26	62	63	26	29	23
Chemelot BKG 06	NL-200400161e	Production of nitric acid	16	14	17	18	30	11
Chemelot BKG 07	NL-200400161f	Production of nitric acid	35	56	76	1	3	2
Chemelot BKG 08	NL-200400161g	Combustion installation	99	66	90	48	86	61
Chemelot BKG 09	NL-200400161h	Production of organic bulk chemicals	171	170	156	168	176	179
Chemelot BKG 10	NL-200400161i	Combustion plant	93	73	84	73	61	92
Chemelot BKG 11	NL-200400161j	Combustion plant	45	49	43	44	48	52
Chemelot BKG 12	NL-200400161k	Combustion plant	52	68	71	79	54	78
Chemelot BKG 13	NL-200400161l	Combustion plant	43	6	4	4	4	5
Chemelot BKG 14	NL-200400161m	Combustion plant	83	69	76	69	68	78
TOTAL			4,802	4,936	4,784	4,794	4,747	4,643

Table 8 Emissions of CO₂ and N₂O by Chemelot site permit B.V. Source: Emissieregistratie¹²

	Carbon dioxide [kt CO ₂ /yr]	Nitrous oxide [kt N ₂ O/yr]	Nitrous oxide [kt CO ₂ eq/yr]	Total [kt CO ₂ eq/yr]
2005	3,556	7.52	2,242	5,798
2010	4,420	2.38	710	5,130
2015	4,784	3.53	1,052	5,836
2016	4,794	2.66	794	5,588
2017	4,747	4.17	1,244	5,991

¹² The CO₂ equivalent emissions have been calculated based on a Global Warming Potential (GWP) of N₂O of 298 tCO₂/tN₂O. There are differences compared to the ETS emissions in

Table 7. One reason for this is that not all N₂O emissions at the Chemelot site are covered by the EU ETS.

2 Fertiliser processes

This section discusses the processes that are currently applied in the fertiliser industry of the Netherlands. Ammonia production, urea production and nitric acid production are discussed in detail.

Fertilisers essentially provide three major plant nutrients (nitrogen, phosphorus and potassium) in plant available forms (European Commission, 2007). Figure 6 presents a general overview of the process routes that are used to produce mineral fertilisers. In the Netherlands, the nitrogen fertilisers are the most important in terms of production volumes and energy consumption. This report focuses on the nitrogen-based fertiliser production at Yara Sluiskil and OCI Nitrogen.

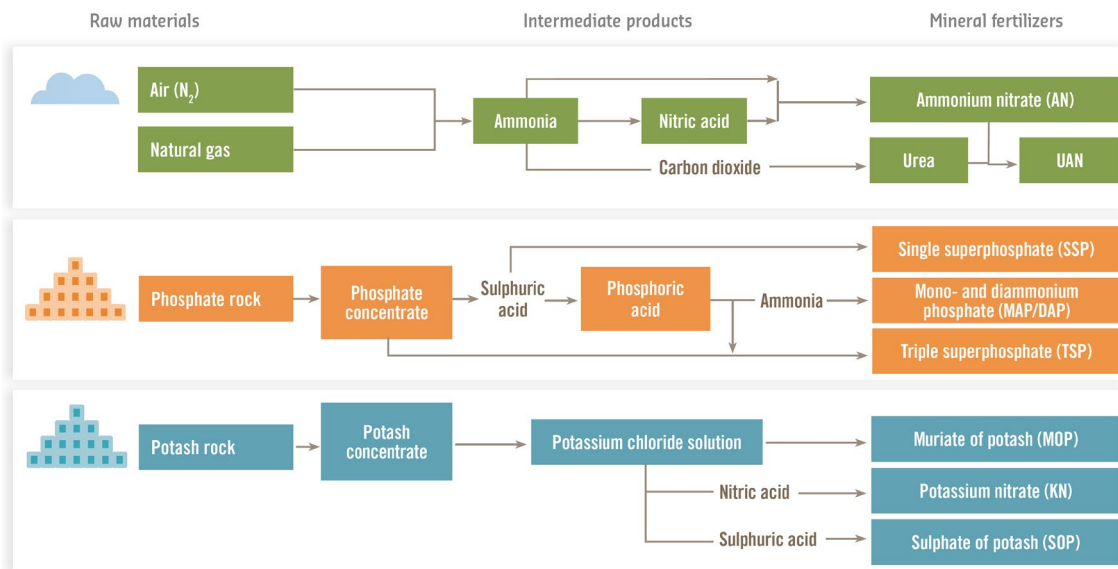


Figure 6 The production of main fertiliser products. Source: (Fertilizers Europe, 2018)¹³

2.1 Ammonia production

Ammonia production is the most energy-intensive process in the fertiliser industry. Ammonia is nearly exclusively produced in large scale plants using the Haber-Bosch process, in which ammonia is synthesised from hydrogen and nitrogen on a Fe-based catalyst. The nitrogen is obtained from the air. The hydrogen is most often produced from steam reforming of natural gas (Bazzanella and Ausfelder, 2017).

Figure 7 gives a schematic overview of the production process for ammonia including the chemical reactions and their input and output flows. The production process involves several steps that will be described in detail below. The description of the ammonia production steps

¹³ This simplified overview does not include Calcium Ammonium Nitrate (CAN), which is obtained by mixing an ammonium nitrate solution with dolomite, limestone or calcium carbonate (European Commission, 2007).

in this section is based on the reference document on Best Available Techniques for the manufacture of large volume inorganic chemicals of the European Commission (European Commission, 2007).

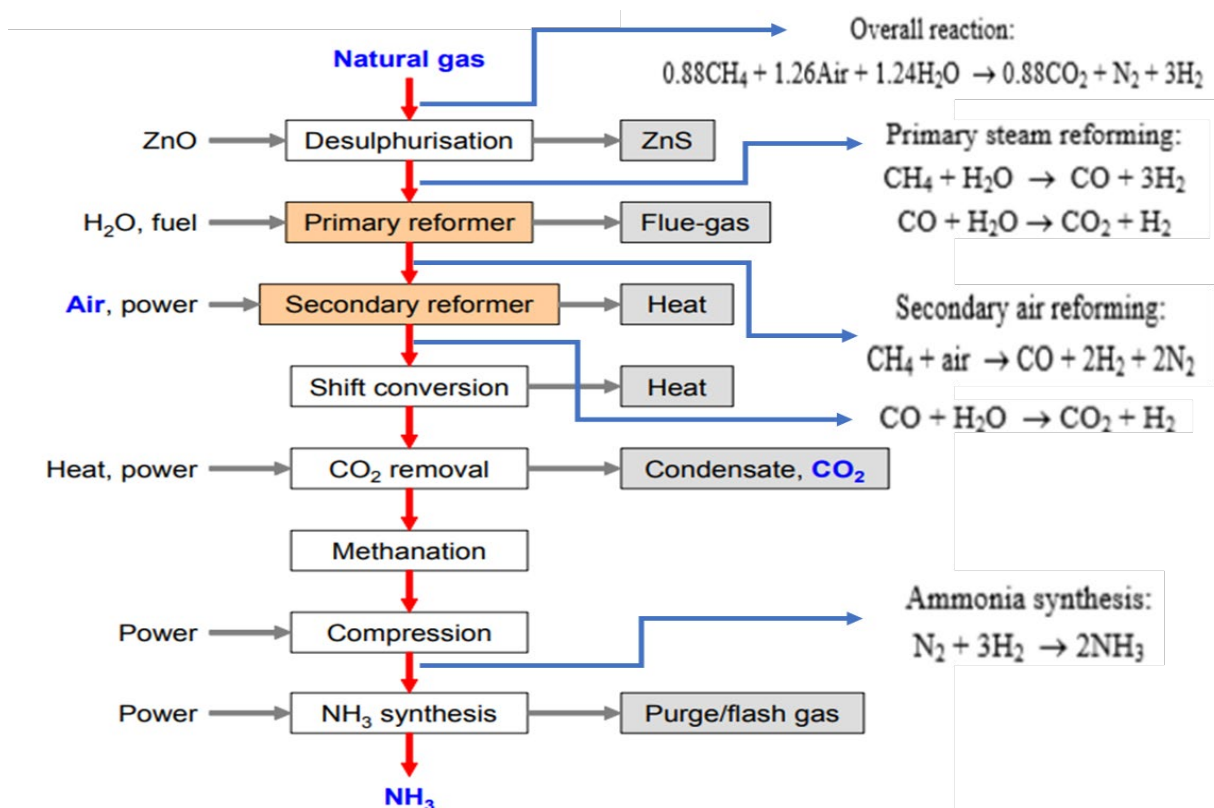


Figure 7 Schematic overview of ammonia production. The blue arrows show the reactions at different steps of the ammonia production process. The red arrows represent the flow of the reaction. Source: (European Commission, 2007)

Table 9 Overview of the ammonia production process. Source (European Commission, 2007)

No	Equations	Step	Heat of reaction
1	$\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2$	Reforming	+206 kJ/mol
2	$\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$	Water gas shift reaction	- 41 kJ/mol
3	$\text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$	Methanation	-206 kJ/mol
4	$\text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$	Methanation	-165 kJ/mol
5	$\text{N}_2 + 3 \text{H}_2 \rightarrow 2\text{NH}_3$	Ammonia synthesis	- 46 kJ/mol

Step 1: Desulfurisation of natural gas

The first step in the ammonia production process is to remove the sulfur content from the natural gas as the catalyst used in the steam reforming process is very sensitive to any sulfur compounds. According to European Commission studies, the sulfur compounds need to be reduced to a concentration of less than 0.15 mg S/Nm³ feed gas. For desulfurisation, the feed gas is pre-heated up to 350–400 °C. Afterwards, hydrogen gas is introduced that reacts with sulfur compounds to form hydrogen sulfide (H₂S). The hydrogen required for the reaction is usually recycled from the synthesis reaction of the plant.

Step 2: Reforming

The reforming is divided into primary and secondary reforming. In primary reforming, the desulfurised gas enters the primary reformer at a temperature in the range of 400–600 °C and is mixed with the steam. The hydrocarbons conversion rate is 60% in the primary reformer in most of the conventional steam reforming processes.

After the primary reformer, the gas mixture enters to the secondary reformer and air is entered at this stage that is needed for the production of ammonia. As only about 60% of feed-gas was reformed in the primary reformer, the reforming process is completed in the secondary reformer. A high temperature is provided in order to increase the conversion rate of hydrocarbons. It is achieved by the internal combustion of part of the reaction gas and the process air that is also a source of nitrogen. Later, it is passed through nickel containing catalysts. About 99% of hydrocarbons are converted in the secondary reformer at a temperature of 500–600 °C, whereas the gas outlet temperature is 1000 °C. Heat is removed by the use of a waste heat boiler and the gas is cooled down to approximately 330–380 °C.

Step 3: Shift conversion

In the shift converter, a reaction is carried out in two steps to convert the 10% CO left over in the secondary reformer into CO₂ and H₂. The main goal of this water gas shift reaction is to produce hydrogen gas. The reaction is exothermic. A copper-based catalyst is currently used for low-temperature water gas shift reactions.

Step 4: Carbon dioxide removal and methanation

The residual CO₂ content in the reaction gas is usually in the range of 50–3,000 ppmv. Both physical and chemical absorption processes are used to remove carbon. In a chemical absorption process by using solvents such as mono ethanolamine (MEA), activated methyl diethanolamine (aMDEA) or in a physical absorption process by using solvents such as glycol dimethylethers (Selexol). Small amounts of CO and CO₂ (e.g. 0.4% CO and 0.01% CO₂), remaining in the synthesis gas, have to be removed to prevent poisoning of the catalyst that is used in the ammonia synthesis step. These compounds are converted into methane in the methanator in the presence of a nickel catalyst at a temperature of 300 °C.

Step 5: Ammonia synthesis

The ammonia synthesis is the last step in the ammonia production plant. It takes place in the presence of an iron-based catalyst at a pressure of 100–150 bar and a temperature that ranges from 300–550 °C. The gas after compression is separated by condensation. The final result is a 10%–20% ammonia yield. The unreacted gas recirculates. To prevent high CH₄ and Argon concentrations these gases are separated and methane is used for the heating of the primary reformer.

According to a benchmarking study of the International Fertilizer Industry Association (IFA), in 2008 the average net energy efficiency in 93 ammonia plants was 36.6 GJ/t NH₃. The top quartile performed in the range of 28 to 33 GJ/t NH₃ (International Fertilizer Industry Association (IFA), 2009).

The best practice technology (BPT) energy use for ammonia production based on natural gas (in final terms) is (IEA, 2009):

- Natural gas (feedstock): +20.7 GJ/t NH₃;
- Natural gas (fuel): +10.9 GJ/t NH₃;
- Electricity: +0.3 GJ/t NH₃;
- Steam: -3.9 GJ/t NH₃;
- Total: +28 GJ/t NH₃.

In this case, there is a net steam export of 3.9 GJ/t NH₃. Modern steam reforming processes can be designed with no steam export or with some export of low/medium pressure steam (Fertilizers Europe, 2000).

The theoretical minimum energy use for the production process is 21.2 GJ/t ammonia. The lower heating value of ammonia is only 18.7 GJ/t, which means that residual heat is generated which may be used for other purposes (IEA/OECD, 2007).

Lako gives the energy efficiency of the ammonia plants in the Netherlands in 2005¹⁴ (Lako, 2009):

- AFA-2 (Geleen): ~31.7 GJ/t NH₃
- AFA-3 (Geleen): ~31.7 GJ/t NH₃
- Yara C (Sluiskil): ~30.5 GJ/t NH₃
- Yara D (Sluiskil): ~30.5 GJ/t NH₃
- Yara E (Sluiskil): ~30.0 GJ/t NH₃

On average, the energy efficiency improvements of ammonia plants in Europe have been limited in the recent past. Between 2004 and 2011, a modest decline of -0.17% per year was observed for a group of 26 European ammonia plants (CEFIC, 2013). In this report, it is assumed that the energy efficiency of the Dutch ammonia plants has remained unchanged since 2005.

Stoichiometrically, CO₂ is formed as coproduct at 0.97 t/CO₂ per t/NH₃. In reality, average direct (feedstock-related) CO₂ emissions from European ammonia plants amount to 1.33 tCO₂/tNH₃. When the hydrogen is supplied by methane steam reforming, the feedstock-related CO₂ emissions are unavoidable (Bazzanella and Ausfelder, 2017).

According to CEFIC, new ammonia plants can achieve an energy demand of 28 GJ/t NH₃. This efficiency is reached by an optimised steam reforming section, a low pressure synthesis loop and better process integration (CEFIC, 2013). Greenfield ammonia plants are expected to reach an energy demand of 27 GJ/t NH₃ by 2030 and 26 GJ/t NH₃ by 2050, assuming high integration with other industrial processes or heat recovery systems (CEFIC, 2013).

2.2 Urea production

Urea is a downstream product of ammonia production. The basic raw materials for urea production are ammonia (NH₃) and carbon dioxide (CO₂). Both can be obtained from a ammonia-synthesis plant, and therefore urea production is often integrated in ammonia plants. To synthesise urea, NH₃ and CO₂ react at high pressure forming ammonium carbamate, which is then dehydrated by applying heat, forming urea and water (European Commission, 2007).

For urea production, NH₃ and CO₂ are fed into a reactor which operates at a temperature of 180–210 °C and a pressure of 150 bar. CO₂ and NH₃ are partially converted into carbamate. In the next step, the unreacted CO₂ and NH₃ are removed, for which CO₂ is used as a stripping agent. During the first reaction, ammonium carbamate is produced. It is a fast and exothermic reaction and takes place at a pressure of 120–250 bar. It is followed by a second reaction that involves the dehydration of ammonium carbamate to produce urea. The second reaction is comparatively slow and endothermic (Fertilizers Europe, 2000).

Usually, the urea solution from the synthesis/recycling stages of the process is concentrated via evaporation or crystallisation to a urea melt. This urea melt is converted to a solid prilled

¹⁴ The values are the sum of the input of natural gas, the net input of steam and the net input of electricity.

or granular product. In some cases, urea is produced solely for melamine production (European Commission, 2007).

Table 10 Overview of the urea production process. Source: (European Commission, 2007)

No	Equations	Step	Heat of reaction
1	$2 \text{ NH}_3 + \text{ CO}_2 \rightarrow \text{ NH}_2\text{COONH}_4$	Ammonium carbamate synthesis	-160 kJ/mol
2	$\text{ NH}_2\text{COONH}_4 \rightarrow \text{ H}_2\text{O} + \text{ NH}_2\text{CONH}_2$	Urea synthesis	+ 41 kJ/mol

The consumption of NH_3 per tonne of urea is estimated to be in the range of 564 to 600 kg (European Commission, 2007). The consumption of CO_2 per tonne of urea is estimated to be in the range of 730–750 kg (European Commission, 2007). To calculate the mass flows for OCI Nitrogen and Yara we assume an input of 0.57 t NH_3 /t urea (Kool, Marinussen and Blonk, 2012) and 0.73 t CO_2 /t urea (Bazzanella and Ausfelder, 2017).

The new 'Ureum 7' plant of Yara Sluiskil is based on the Total Recycling Stripping Process, and uses 80% less electricity than the old urea solution plants 'Ureum 5' and 'Ureum 6'. This is realised by using steam instead of electricity for driving the CO_2 compressor and by using a CO_2 stripping process that works at low pressure (Gedeputeerde Staten van Zeeland, 2009b).

The energy demand of isolated urea production is hard to estimate, because it is usually highly integrated in the ammonia plant. Based on best practice technology values, it is assumed that 2.2 GJ of steam and 0.3 GJ of electricity are required to produce one tonne of urea (IEA, 2009). Schyns reports a weighted EU average energy consumption of 5,06 GJ/t urea (performance in 2003) (Schyns, 2006).

2.3 Nitric acid production

In Europe, most of the nitric acid (HNO_3) is produced by the high-temperature catalytic oxidation of ammonia. This process typically consists of three steps: ammonia oxidation, nitric oxide oxidation, and absorption (Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut, 2009).

Nitric oxide is synthesised from the oxidation of ammonia. Subsequently, it is oxidised to nitrogen dioxide. The nitrogen dioxide is absorbed in water to form nitric acid and nitric oxide. The nitric oxide is cycled back for re-oxidation (CEFIC, 2013).

Table 11 Overview of the nitric acid production process. Source (European Commission, 2007)

No	Equations	Step
1	$4 \text{ NH}_3 + 5 \text{ O}_2 \rightarrow 4 \text{ NO} + 6 \text{ H}_2\text{O}$	Oxidation of NH_3
2	$2 \text{ NO} + \text{ O}_2 \rightarrow 2 \text{ NO}_2$	Oxidation of NO
3	$3 \text{ NO}_2 + \text{ H}_2\text{O} \rightarrow 2 \text{ HNO}_3 + \text{ NO}$	Absorption

The input of ammonia is 0.27 t NH_3 /t HNO_3 . The conversion efficiency from ammonia to nitric acid is approximately 94% (Yara HESQ/ TK Jenssen, 2011).

Heat can be recovered from the nitric acid production process, which is highly exothermal. The reaction of NH_3 to HNO_3 theoretically releases 6.3 GJ/t HNO_3 . However, energy losses and conversion of thermal energy to electrical energy in a steam turbine can reduce the net energy export (European Commission, 2007).

Lako cites a benchmark study of 83 nitric acid producers in which the energy export varied from +1.83 GJ/t HNO_3 to -3.8 GJ/t HNO_3 (Lako, 2009)¹⁵. According to Ecofys and JRC, energy recovery in dual pressure plants amounts to around 2.4 GJ/t HNO_3 (Overgaag, Harmsen and Schmitz, 2009). Because of the wide range of the literature values, to calculate the energy flows for OCI Nitrogen and Yara it is assumed that there is no net energy export.

In nitric acid production, nitrous oxide (N_2O) is generated as a by-product (European Commission, 2007). N_2O is a strong greenhouse gas. Using modern technology N_2O emissions can be highly reduced. The BAT N_2O emission level for new plants has a range of 0.12 – 0.6 kg N_2O /t HNO_3 and for existing plants of 0.12 – 1.85 kg N_2O /t HNO_3 (Overgaag, Harmsen and Schmitz, 2009).

2.4 Overview of energy flows, mass flows and greenhouse gas emissions

The energy consumption at OCI Nitrogen and Yara Sluiskil can be estimated by combining the activity levels and the specific energy consumption of the processes at the plants. The characteristics that have been discussed in Chapters 1 and 2 can also be used to estimate the mass flows and the greenhouse gas emissions.

The operation of steam turbines and gas turbines (e.g. for compression of synthesis gas or electricity production) is strongly integrated in the ammonia production process (Boot, 1994). Here, these installations are considered to be part of the ammonia production process. Similarly, the production of end products is strongly integrated. For example, the ammonia plants can export steam to the urea plants. Some of the processes are exothermal, which complicates a detailed analysis at the installation level. The calculations are limited to the processes for ammonia, urea and nitric acid production and are based on 8,000 hours of operation per year.¹⁶

Table 12 shows estimated energy flows, mass flows and greenhouse gas emissions at Yara Sluiskil in 2017. Table 13 shows the results for OCI Nitrogen. The total estimated consumption of natural gas by both companies is 94.4 PJ (2.98 billion Nm^3) and the total estimated net consumption of electricity is 1.0 PJ (0.28 TWh). According to the energy balances of Statistics Netherlands (CBS), the consumption of natural gas of the fertiliser sector was 96.3 PJ (3.04 billion Nm^3) and the net consumption of electricity was 1.8 PJ (0.50 TWh).

The greenhouse gas emissions of OCI Nitrogen in Table 13 (2.3 Mt CO_2eq) are somewhat higher than the EU ETS emissions shown in Table 7 (1.9 Mt CO_2eq). The greenhouse gas emissions of Yara Sluiskil in Table 12 (3.4 Mt CO_2eq) are somewhat lower than the EU ETS emissions shown in Table 4 (3.8 Mt CO_2eq). No public information is available on the production and energy efficiency of the companies.

¹⁵ The negative value implies that there is energy import.

¹⁶ Most ammonia plants are designed to be available for about 8,000 hours per year (Morgan, 2013).

Table 12 Estimated energy consumption and emissions of ammonia, urea and nitric acid production at Yara Sluiskil B.V. in 2017

	Ammonia plant C	Ammonia plant D	Ammonia plant E	Urea	Nitric acid	Total
Capacity [kt product/year]	449	639	731	1,300	1,500	-
Operating hours [h]	8,000	8,000	8,000	8,000	8,000	-
Production [kt product/year]	410	584	668	1,187	1,370	-
Input of ammonia [tNH ₃ /t product]	0	0	0	0.57	0.27	-
Input of ammonia [kt]	0	0	0	677	370	1,047
Input of CO ₂ [tCO ₂ /t product]	0	0	0	0.73	0	-
Input of CO ₂ [Mt]	0.0	0.0	0.0	0.9	0.0	0.9
Input of natural gas (fuel) [GJ/t product]	13.4	13.4	12.9	0.0	0.0	-
Input of natural gas (fuel) [PJ]	5.5	7.8	8.6	0.0	0.0	22
Input of natural gas (feedstock) [GJ/t product]	20.7	20.7	20.7	0.0	0.0	-
Input of natural gas (feedstock) [PJ]	8.5	12.1	13.8	0.0	0.0	34
Input of natural gas (total) [GJ/t product]	34.1	34.1	33.6	0.0	0.0	102
Input of natural gas (total) [PJ]	14.0	19.9	22.4	0.0	0.0	56
Net input of steam [GJ/t product]	-3.9	-3.9	-3.9	2.2	0.0	-
Net input of steam [PJ]	-1.6	-2.3	-2.6	2.6	0.0	-3.9
Net input of electricity [GJ/t product]	0.3	0.3	0.3	0.3	0.1	-
Net input of electricity [PJ]	0.1	0.2	0.2	0.4	0.1	1.0
CO ₂ emission (total) [tCO ₂ /t product]	1.9	1.9	1.9	0.0	0.0	-
CO ₂ emission (total) [Mt CO ₂]	0.8	1.1	1.3	0.0	0.0	3.2
CO ₂ emission (high purity CO ₂) [tCO ₂ /t product]	1.3	1.3	1.3	0.0	0.0	4.0
CO ₂ emission (high purity CO ₂) [Mt CO ₂]	0.5	0.8	0.9	0.0	0.0	2.2
CO ₂ emission (combustion) [tCO ₂ /t product]	0.6	0.6	0.6	0.0	0.0	1.8
CO ₂ emission (combustion) [Mt CO ₂]	0.2	0.3	0.4	0.0	0.0	1.0
N ₂ O emission [kg N ₂ O/t product]	0.0	0.0	0.0	0.0	0.6	-
N ₂ O emission [tN ₂ O]	0	0	0	0	780	780
N ₂ O emission [Mt CO ₂ eq]	0.0	0.0	0.0	0.0	0.2	0.2
Greenhouse gas emission [Mt CO ₂ eq]	0.8	1.1	1.3	0.0	0.2	3.4

Table 13 Estimated energy consumption and emissions of ammonia-, urea- and nitric acid production, at OCI Nitrogen B.V. in 2017

	Ammonia (AFA-2 and AFA-3)	Urea	Nitric acid	Total
Capacity [kt product/year]	1,184	525	965	-
Operating hours [h]	8,000	8,000	8,000	-
Production [kt product/year]	1,081	479	881	2,442
Input of ammonia [tNH ₃ /t product]	0	0.57	0.27	-
Input of ammonia [kt]	0	273	238	511
Input of CO ₂ [tCO ₂ /t product]	0	0.73	0	-
Input of CO ₂ [Mt]	0.0	0.4	0.0	0.4
Input of natural gas (fuel) [GJ/t product]	14.6	0.0	0.0	-
Input of natural gas (fuel) [PJ]	15.8	0.0	0.0	15.8
Input of natural gas (feedstock) [GJ/t product]	20.7	0.0	0.0	20.7
Input of natural gas (feedstock) [PJ]	22.4	0.0	0.0	22.4
Input of natural gas (total) [GJ/t product]	35.3	0.0	0.0	35.3
Input of natural gas (total) [PJ]	38.1	0.0	0.0	38.1
Net input of steam [GJ/t product]	-3.9	2.2	0.0	-
Net input of steam [PJ]	-4.2	1.1	0.0	-3.2
Net input of electricity [GJ/t product]	0.3	0.3	0.1	-
Net input of electricity [PJ]	0.3	0.1	0.1	0.5
CO ₂ emission (total) [tCO ₂ /t product]	2.0	0.0	0.0	-
CO ₂ emission (total) [Mt CO ₂]	2.2	0.0	0.0	2.2
CO ₂ emission (high purity CO ₂) [tCO ₂ /t product]	1.3	0.0	0.0	1.3
CO ₂ emission (high purity CO ₂) [Mt CO ₂]	1.4	0.0	0.0	1.4
CO ₂ emission (combustion) [tCO ₂ /t product]	0.7	0.0	0.0	0.7
CO ₂ emission (combustion) [Mt CO ₂]	0.7	0.0	0.0	0.7
N ₂ O emission [kg N ₂ O/t product]	0.0	0.0	0.6	-
N ₂ O emission [tN ₂ O]	0	0	502	502
N ₂ O emission [Mt CO ₂ eq]	0.0	0.0	0.1	0.1
Greenhouse gas emission [Mt CO ₂ eq]	2.2	0.0	0.1	2.3

3 Fertiliser products and application

This section discusses some of the main products of the Dutch fertiliser industry, their applications and product markets.

3.1 Products of the fertiliser industry

According to the sector association *Fertilizers Europe*, the total European fertiliser production in 2016 was 16.6 million tonnes. Of this amount, 73% consisted of nitrogen (N) fertilisers, 11% of phosphorus (P_2O_5) fertilisers and 16% of potassium (K_2O) fertilisers.

The main intermediate products of the nitrogen fertiliser industry are ammonia and nitric acid:

- **Ammonia (NH_3)** is mainly used for the production of fertilisers. Ammonia is also widely used to produce synthetic materials such as melamine, caprolactam and acrylonitrile. It is used as a raw material for resins and pharmaceuticals and as a refrigerant (KPMG, TNO, ECORYS, 2004). The sector association *Meststoffen Nederland* ('fertilisers Netherlands') estimates that of the total Dutch ammonia production capacity of 2.6 million tonnes, 1.6 to 1.9 million tonnes are used for the production of fertilisers (Meststoffen Nederland, 2015).
- **Nitric acid (HNO_3)** is also mainly used to produce fertilisers. In addition, nitric acid is used to produce explosives and chemicals such as caprolactam (European Commission, 2007). Nitric acid is also used for industrial cleaning (ISPT, 2017).

The European consumption of nitrogen fertilisers can be divided into nitrates (45%), urea (23%), Urea Ammonium Nitrate (13%), compound fertilisers (13%) and others (6%)¹⁷:

- **Ammonium nitrate (AN)** is produced by neutralising nitric acid with ammonia in an exothermic process. The released process heat is used to preheat the nitric acid, to evaporate water or ammonia, and to produce steam (Boot, 1994).
- **Calcium Ammonium Nitrate (CAN)** is obtained by mixing an ammonium nitrate solution with dolomite, limestone or calcium carbonate (European Commission, 2007).
- **Urea** is used in fertilisers. It is also used as a feedstock for melamine, resins, medicines and cosmetics (ISPT, 2017). Urea can also be used for DeNO_x applications in power plants. Diluted urea is also used to prevent NO_x emissions of trucks, cars and vessels (ISPT, 2017). For these purposes, urea solutions (such as Ad Blue) are made from concentrated urea solution by thinning it with demineralised water (Gedeputeerde Staten van Zeeland, 2008).
- For the production of **Urea Ammonium Nitrate (UAN)**, concentrated urea and ammonium nitrate solutions are measured, mixed and then cooled (European Commission, 2007).
- **Compound fertilisers** contain more than one of the three basic nutrients N, P_2O_5 and K_2O .

¹⁷ Shares of fertilisers for agricultural use in 2016/2017 based on Fertilizers Europe (Fertilizers Europe, 2018).

Solid fertiliser products are made by prilling and granulation (European Commission, 2007). The formation of spheres by the solidification of liquid droplets of fertiliser material is known as prilling. The prilling process is used to produce prills of ammonium nitrate and urea. Granulation requires a more complicated plant and a variety of equipment, including rotating pans and drums and fluidised beds.

Table 14 Inputs of production processes in the nitrogen fertiliser industry. Source: (Kool, Marinussen, & Blonk, 2012)

Product	Input	Value
Ammonium nitrate (AN)	Ammonia	0.22 t NH ₃ /t AN
	Nitric acid	0.81 t HNO ₃ /t AN
Urea Ammonium Nitrate (UAN)	Urea	0.35 t urea/t UAN
	Ammonium nitrate	0.46 t AN/t UAN
Calcium Ammonium Nitrate (CAN)	Dolomite	0.24 t dolomite/t CAN
	Ammonium nitrate	0.76 t AN/t CAN
Ammonium Sulfate (AS)	Ammonia	0.26 t NH ₃ /t AS
	Sulfuric acid	0.59 t H ₂ SO ₄ /t AS

3.2 Product markets

The Dutch production of nitrogen compounds mainly takes place for fertiliser consumption in the agriculture sector of Western Europe. There is large import and export of fertilisers (De Bruyn, Koopman, Van Lieshout, Croezen and Smit, 2014).

The industry has to deal with increasing costs for greenhouse gas emissions as a result of the EU Emissions Trading System (EU ETS). Other developments that are important for the European ammonia and fertiliser industry are (De Bruyn, Koopman, Van Lieshout, Croezen and Smit, 2014):

- Changes in the costs of natural gas compared to other regions;
- Efficiency improvements in the use of fertilisers, which reduce the demand per unit of crop;
- Increased treatment of manure, which improves the availability of the nutrients for agricultural crops and reduces the demand for fertilisers;
- An increasing demand for agricultural products to produce biomass for energy or the chemical industry, which can increase the demand for nitrogen fertilisers.

In the Netherlands, animal manure and fertilisers are the main sources of nitrogen and phosphate for agricultural land. In the period 2005–2014, the supply of animal manure has remained stable and the supply of mineral fertilisers was reduced from an average of 135 kg N per hectare to an average of 104 kg N per hectare. The amount of phosphate fertiliser has reduced from 24 kg phosphate per hectare to 6 kg phosphate per hectare (Velthof, et al., 2017).

In its results report, OCI N.V. presents benchmark prices¹⁸ for main products of the fertiliser industry (OCI N.V., 2018a):

1. Ammonia (NW Europe, FOB): USD 278/t;
2. Ammonia (US Gulf Tampa contract): USD 267/t;
3. Granular Urea (Egypt, FOB): USD 244/t;
4. CAN (Germany, CIF): USD 175/t;
5. UAN (France, FOT): USD 153/t;
6. UAN (US Midwest, FOB): USD 231/t.

¹⁸ Prices for Q2 2018, based on CRU, Argus.

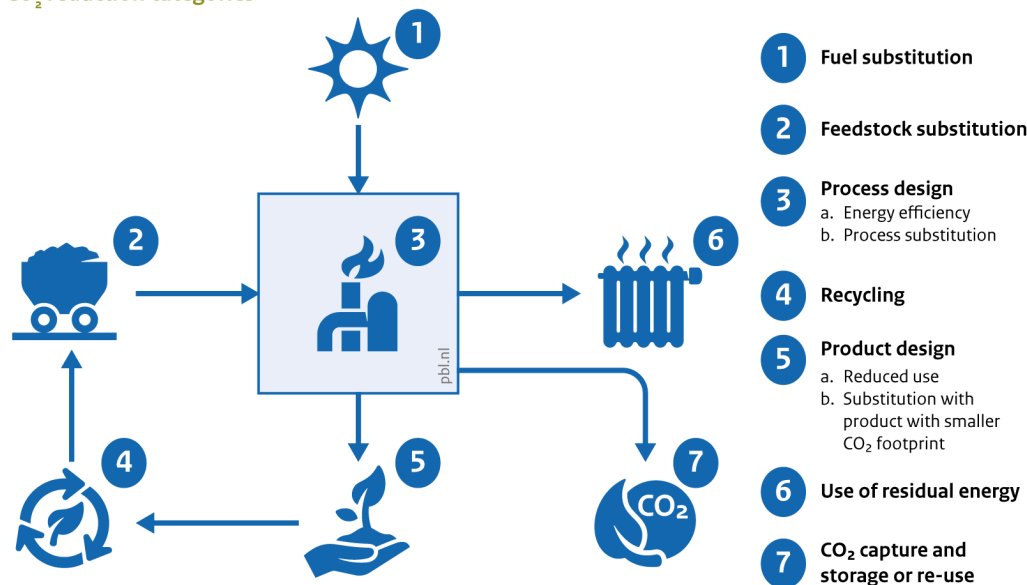
4 Options for decarbonisation

This section discusses options for decarbonisation of the fertiliser industry. Some of the main decarbonisation options are using hydrogen with a lower CO₂ footprint (e.g. green hydrogen from electrolysis) and carbon capture and storage.

The options that are discussed are:

1. Using hydrogen with a lower CO₂ footprint;
 - Green hydrogen produced from electrolysis of water;
 - Blue hydrogen produced from natural gas with carbon capture and storage;
 - Hydrogen from biomass gasification;
 - Other hydrogen production processes;
 - Hydrogen distribution infrastructure;
2. Carbon capture and storage;
 - Capture and storage of CO₂ emissions from existing processes;
3. Other decarbonisation options;
 - Reduced use of fertilisers;
 - Energy efficiency improvements;
 - Biogas;
 - Heat and CO₂ distribution to other sectors (built environment, greenhouse horticulture);
 - Solid state ammonia synthesis;
 - Abatement of nitrous oxide.

CO₂ reduction categories



Bron: PBL

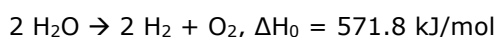
Figure 8 CO₂ reduction categories

4.1 Using hydrogen with a lower CO₂ footprint

Green hydrogen produced from electrolysis of water

In the conventional ammonia production process, ammonia is produced by steam methane reforming of natural gas combined with Haber-Bosch NH₃ synthesis. Alternatively, the hydrogen that is required for the Haber-Bosch process can be produced by electrolysis of water. In an electrolyser, an electric current splits water into hydrogen and oxygen. No plants using electrolysis to produce ammonia are currently operational (ISPT, 2017).

Electrolysers operate by passing an electrical current between an anode and a cathode via an electrolyte. Catalysts are used to reduce the electricity consumption. Electrolysis of H₂O is used to supply the H₂ and an air separation unit is used to supply nitrogen (N₂). An air separation unit is required, as the supply of pure nitrogen due to oxygen consumption of process air in the secondary reformer is not available anymore. The N₂ from the air separation unit and H₂ are mixed for the synthesis of NH₃ (Bazzanella and Ausfelder, 2017).



As the endothermic methane steam reforming is omitted, the corresponding process-related emissions are reduced (Bazzanella and Ausfelder, 2017). On the other hand, no excess steam is generated in the secondary reformer which can be used in other processes.

Compressors are needed to compress hydrogen and nitrogen to a pressure of 100–250 bar required for ammonia synthesis as well as for refrigeration (Bazzanella and Ausfelder, 2017).

Three main technological routes for electrolysis are (Bazzanella and Ausfelder, 2017):

1. alkaline electrolysis;
2. Proton-Exchange-Membrane (PEM) electrolysis, and
3. high-temperature solid-oxide electrolysis.

Alkaline electrolysis and PEM electrolysis are low temperature electrolysis technologies that are commercially available, but not yet at larger than 100 MW scale. High temperature electrolysis technology requires less electricity, but additional heat input. Currently, high temperature electrolysers are not commercially available (ISPT, 2017).

The main difference between electrolytic ammonia and steam reforming is the production route for hydrogen and nitrogen. The reactors and compressors used in the Haber Bosch process are the same as those used in steam reforming or partial oxidation (Morgan, 2013).

Electrolysis of water consumes more energy per mole of hydrogen produced than steam reforming. The theoretically minimal required electricity input for hydrogen production is 39.4 kWh per kg H₂ produced at 0 °C and 1 bar.¹⁹ In practice, the losses are higher. The current Best Available Technique (BAT) specific power consumption for low temperature electrolysers is 53 kWh per kg H₂ produced (ISPT, 2017).

Bazzanella and Ausfelder estimate that around 1.4 MWh/t NH₃ is needed for compressors and 0.33 MWh/t NH₃ for the air separation unit. Investments for the ASU are estimated to be EUR 27/t NH₃ (Benner, Van Lieshout and Croezen, 2011). The existing installations for ammonia synthesis can be used (Stork, De Beer, Lintmeijer and Den Ouden, 2018), but adjustments are needed for the new feed-ins before the synthesis. The OPEX excluding

¹⁹ In case of solid-oxide electrolysis, the electrical input can be lower, if water is supplied as steam using suitable process heat sources (Bazzanella and Ausfelder, 2017).

feedstocks are dominated by the maintenance costs (ISPT, 2017). Here, the OPEX is assumed to be 3% of the CAPEX.

The investment costs for hydrogen electrolyzers are going down fast. Ecofys and Berenschot have assumed that the investment costs for hydrogen electrolysis were EUR 525/kW in 2018 (Stork, De Beer, Lintmeijer and Den Ouden, 2018). Table 17 shows the costs and energy consumption of electrolysis based on the assumptions described before, for 4,500 and 8,000 operating hours. The total electricity demand is 40 GJ/t NH₃. For comparison, OCI Nitrogen has estimated that 37–44 GJ of electricity is needed per tonne of NH₃ (De Geus, 2017).

Table 15 Costs and energy requirements for electrolysis

	Yara Sluiskil	Yara Sluiskil	OCI Nitrogen	OCI Nitrogen
Operating hours	4,500	8,000	4,500	8,000
Production of ammonia [kt/year]	1,661	1,661	1,081	1,081
Hydrogen required [t/t ammonia] ²⁰	0.178	0.178	0.178	0.178
Hydrogen required [kt/year]	296	296	192	192
Electricity demand for electrolysis [kWh/kg hydrogen]	53	53	53	53
Electricity demand for electrolysis [kWh/kg ammonia]	9.4	9.4	9.4	9.4
Electricity demand for electrolysis [GJ/t ammonia]	34.0	34.0	34.0	34.0
Electricity demand for electrolysis [TWh]	15.7	15.7	10.2	10.2
Electricity for compressors and air separation unit [MWh/t ammonia]	1.73	1.73	1.73	1.73
Electricity for compressors and air separation unit [GJ/t ammonia]	6.2	6.2	6.2	6.2
Electricity for compressors and air separation unit [TWh]	2.9	2.9	1.9	1.9
Electricity demand (total) [GJ/t ammonia]	40.2	40.2	40.2	40.2
Electricity demand (total) [TWh]	18.5	18.5	12.1	12.1
Capacity of electrolyzers [GW]	4.1	2.3	2.7	1.5
Investments electrolyzers [euro/kW]	525	525	525	525
Investments air separation unit [EUR/t ammonia/year]	27	27	27	27
Investments electrolyzers [EUR million]	2,164	1,217	1,408	792
Investments air separation unit [EUR million]	45	45	29	29
Investments (total) [EUR million]	2,208	1,262	1,438	821
O&M costs [EUR million/year]	66	38	43	25

The investments required for electrochemical-based NH₃ production are higher than the investments for conventional NH₃ production based on Steam Methane Reforming. The production costs of large electrolyzers are expected to decrease due to (ISPT, 2017):

- Scaling up;
- Optimisation of production processes;
- Technological development;
- Stimulation of market demand;
- Development of new types of electrolyzers.

²⁰ 178 kg hydrogen is needed per tonne of ammonia (Bazzanella and Ausfelder, 2017).

Despite being largely modular, electrolysers exhibit economies of scale as the compressors, gas holding tanks, transformers and balance of plant equipment are scaled up (Morgan, 2013). Flexible electrochemical H₂ production is proven technology, but needs to be made suitable for large scale applications (ISPT, 2017).

Lifetime stack replacement costs vary between 60%–65% of electrolyser costs. The time to replacement can be estimated to be 80,000 hours of operation for low temperature units or 40,000 operating hours for high temperature units (ISPT, 2017).

The Institute for Sustainable Process Technology (ISPT) published a study on the electrochemical production of NH₃ and the storage of electricity in ammonia. From this 'Power to Ammonia' study (ISPT, 2017), OCI Nitrogen concludes that CO₂-neutral ammonia produced in an electrochemical way from sustainable electricity will be a feasible alternative for ammonia produced from natural gas in the longer term, but that this is not economically feasible currently. The consortium has outlined an innovation and R&D plan to work towards a profitable process by 2030 (OCI N.V., 2018a).

A small scale pilot plant for Power-2-Ammonia at OCI Nitrogen (either at Geleen or Europoort) has been studied as a business case (ISPT, 2017). The infrastructure for chemical processes and NH₃ is already present, which reduces the investment in utilities and handling, as well as lead time costs and complexity of permits. The investments needed for 20 kt NH₃ production have been estimated to be in the order of 30 million euro. OCI Nitrogen has estimated that a large-scale electrolysis pilot unit of 100 MW requires an investment of EUR 50 million (Van Lieshout, Rooijers and Croezen, 2018).

OCI concludes that the electrification route could be profitable before 2030 if investments, mainly in the electrolysers, could be reduced significantly, the pricing of renewable NH₃ would be significantly higher, and the costs for CO₂ emission would be higher (ISPT, 2017).

The capacity of the current electricity grid at OCI Nitrogen is not sufficient to switch to production exclusively based on electrolysis. To enable this, either the grid capacity has to be increased or hydrogen has to be supplied to OCI Nitrogen by pipeline. According to OCI Nitrogen, the electricity grid at Chemelot can handle an additional 24 MW. The ammonia plant can handle an additional 12 MW (De Geus, 2017).

The CO₂ footprint of electrochemically produced NH₃ depends on the greenhouse gas emission intensity of electricity generation. If the electricity is produced from fossil fuels, the CO₂ footprint can be higher than of conventional NH₃ (ISPT, 2017). When hydrogen is made with electrolysis, other sources of CO₂ are needed to make urea or supply CO₂ for other purposes. The CO₂ is no longer supplied by the conventional ammonia process (Stork, De Beer, Lintmeijer and Den Ouden, 2018).

Blue hydrogen produced from natural gas with carbon capture and storage

Blue hydrogen is produced from natural gas, usually via steam-reforming, with carbon capture and storage. CE Delft has studied the techno-economic feasibility and sustainability of blue hydrogen (Van Cappellen, Croezen and Rooijers, 2019). Carbon capture and storage is discussed in more detail in Section 4.2.

Hydrogen from biomass gasification

Gasification of (ligno-)cellulose from wood can produce a syngas, which is a mixture of hydrogen, carbon monoxide and carbon dioxide. This gas can be used as a feedstock to produce ammonia (Stork, De Beer, Lintmeijer and Den Ouden, 2018). A major limiting factor

for this technology is the availability of the feedstock (CEFIC, 2013). Biomass gasification requires a high capital expenditure for process equipment (OECD/IEA, 2017).

OCI Nitrogen is studying the feasibility to use biomass or municipal solid waste stream gasification technology to make syngas that can be converted to ammonia (OCI N.V., 2018a).

Other hydrogen production processes

Bazzanella and Ausfelder (Bazzanella and Ausfelder, 2017) discuss other processes to production hydrogen, which still have rather low TRL levels.

- Methane pyrolysis (thermal decomposition of methane) has a reduced energy demand and could be based on renewable methane. This process produces solid carbon and hydrogen and has a TRL level of 4–5.
- Thermochemical processes in which high-temperature heat is used to split water. The heat could be supplied by solar heat or waste heat. The TRL level is 4.
- Photocatalytic processes have a TRL level of 2–3.

Hydrogen distribution infrastructure

Instead of producing hydrogen on the site, it is possible to use hydrogen that is supplied from elsewhere. Chemelot considers hydrogen infrastructure a possible promising route to substitute the current feedstocks by sustainable alternatives (Chemelot Site Permit B.V., 2018). A group of companies in the Delta region (including Yara) see the development of a future-oriented energy infrastructure for both electricity and CO₂-free gas (predominantly hydrogen) as a key priority. According to them, the development of a regional open network hydrogen infrastructure will enable reduction of greenhouse gas emissions and decrease the dependency on carbon capture and storage in the long term (Van Lieshout, Rooijers and Croezen, 2018). A first estimate of the investment required to connect all Smart Delta Resources (SDR) companies between Zeeland Refinery in the Sloe area and Arcelor Mittal in the southern part of North Sea Port by a regional H₂/O₂ net is EUR 60–70 million (Van Lieshout, Rooijers and Croezen, 2018).

Dow, Yara and ICL-IP have recently realised a hydrogen infrastructure between their companies. Hydrogen that is released as a side-product from cracker processes at Dow serves as a feedstock for the production processes at Yara and ICL-IP. The hydrogen is transported using a gas pipeline of Gasunie Transport Services (GTS) that was no longer in use (Yara Sluiskil N.V. , 2016). The construction was started in May 2018, and involved modification of the gas pipeline and the connections at Dow and Yara (Dow Benelux, 2018).

The amount of hydrogen that can be supplied in the first step is 4.5 kt/year. The emission reduction is estimated to be approximately 10 kt CO₂ per year (Rijksoverheid en Private Partijen, 2016). In a second phase, Yara can use more hydrogen from Dow, but this requires additional investments. Yara is studying the feasibility of this second phase (Dow Benelux, 2018). When the complete project is finished, the CO₂ reduction could amount to 20–40 kt CO₂ (Yara Sluiskil N.V. , 2016).

4.2 Carbon capture and storage

Ammonia plants produce large flows of almost pure CO₂ gases, which are well suited for carbon capture and storage (CCS). The CO₂ is already captured, but needs to be compressed and transported to a storage location.

The first Dutch studies into CCS projects were carried out in 1988 (Hendriks, Koornneef, & Oude Lohuis, 2015). In 2004, the first injection of CO₂ in a Dutch gas field under the sea floor took place (Hendriks, Koornneef, & Oude Lohuis, 2015). Afterwards, there have been several CCS initiatives that were not followed through (e.g. in Chemelot, Barendrecht and the North of the Netherlands). In 2017, Uniper and Engie announced to end the ROAD project (Port of Rotterdam, 2017).

Carbon emissions from ammonia production arise from the flue gases of the combustion processes and from the reforming reaction. The CO₂ released from the reforming step is highly concentrated and is captured. Part of this CO₂ is already used as feedstock for urea production or other downstream utilisation. The CO₂ from exhaust gases of heat generation are more difficult to capture and are currently emitted to the air.

CEFIC gives the investment costs and energy requirements for CCS as shown in Table 16. The costs of CCS are lower when the point source of the emissions are larger and the flow of the CO₂ is more concentrated.

Table 16 Costs for CCS on pure sources and combustion sources (CEFIC, 2013)

	Year of assessment	Capture rate	Cost item	Plant size [Mt CO ₂ /year]	Investment costs [EUR ₂₀₁₀ /t CO ₂ annually captured]	Heat requirements [GJ/t CO ₂ captured]	Electricity requirements [GJ/t CO ₂ captured] ²¹
CCS on pure sources (process-related emissions)	2020	100%	Capture and compression	<0.8	100	0	0.4
				0.8	40		
				>0.8	30		
			Transport	All	80		
			Storage	All	60		
CCS on combustion sources	2020	85%	Capture and compression	0.13	1,020	3.2	0.48
				0.25	714		
				0.5	500		
				1.2	300		
			3.0	200			
			Transport	All	80		
			Storage	All	60		
			CCS on combustion sources	2030	85%		
0.25	429						
0.5	300						
1.2	225						
3.0	125						
Transport	All	70					
Storage	All	60					
CCS on combustion sources	2050	85%				Capture and compression	0.13
			0.25	229			
			0.5	160			
			1.2	130			
			3.0	90			
			Transport	All	50		
			Storage	All	60		

Table 17 shows the amounts of CO₂ that can potentially be stored. Around 70% of the CO₂ emissions are high purity streams. According to Yara, the amount of CO₂ for carbon capture

²¹ Electricity for drying and cleaning is not included.

and utilisation was 1.4 Mt CO₂ in 2017 (Yara Sluiskil B.V. , 2018). Of the pure CO₂ produced at OCI Nitrogen around 70% is utilised (De Geus, 2017).

Table 17 CO₂ emissions at Yara Sluiskil and OCI Nitrogen in 2017

[Mt CO ₂]	Yara Sluiskil	OCI Nitrogen
CO ₂ emission (total)	3.2	2.2
- of which CO ₂ from combustion	1.0	0.7
- of which high purity CO ₂	2.2	1.4
Utilisation of high purity CO ₂ ²²	1.4	1.0

Table 18 shows the resulting estimated costs and energy requirements for capture and compression of CO₂. It is also required that there is infrastructure to transport and store the CO₂. The Port of Rotterdam, Energie Beheer Nederland (EBN) and Gasunie have taken the initiative for the Porthos project. Their ambition is to realise basic infrastructure for transport and storage of CO₂ in the Rotterdam port area (Vries, 2018).

Table 18 Costs and energy requirements for capture and compression of CO₂²³

	Yara Sluiskil			OCI Nitrogen		
	High purity CO ₂	CO ₂ from combustion (2020)	CO ₂ from combustion (2030)	High purity CO ₂	CO ₂ from combustion (2020)	CO ₂ from combustion (2030)
CO ₂ emission [Mt]	2.2	1.0	1.0	1.4	0.7	0.7
Capture rate	100%	85%	85%	100%	85%	85%
CO ₂ captured [Mt]	2.2	0.8	0.8	1.4	0.6	0.6
Investment costs [EUR ₂₀₁₀ /t CO ₂ annually captured] ²⁴	30	364	249	30	437	276
Heat requirements [GJ/t CO ₂ captured]	0	3.2	0	0	3.2	0
Electricity requirements [GJ/t CO ₂ captured]	0.4	0.48	1.13	0.4	0.48	1.13
Investment [EUR ₂₀₁₀ million]	66	302	206	43	268	169
Heat requirements [PJ]	0.0	2.7	0.0	0.0	2.0	0.0
Electricity requirements [PJ]	0.9	0.4	0.9	0.6	0.3	0.7

The TRL of deploying CCS on process emissions from the steam methane reforming process (i.e. on high purity CO₂ streams) is 6–7 (WSP/Parsons Brinckerhoff, DNV GL, 2015). The TRL of capture of CO₂ from combustion gases and subsequent geological storage is 6 (WSP/Parsons Brinckerhoff, DNV GL, 2015). For large scale CCS projects, long lead times have to be reckoned with (often at least seven years) (EBN, Gasunie, 2017).

²² CO₂ that is used in follow-up processes, including liquefaction.

²³ The calculations are based on the cost data in Table 16.

²⁴ Based on linear interpolation of the investment costs in Table 16.

4.3 Other decarbonisation options

Reduced use of fertilisers

Greenhouse gas emissions can be reduced if the same amount of food is consumed with less input of mineral fertilisers. Measures that can contribute to this are reduction of food waste, substitution of mineral fertilisers with organic fertilisers, precision agriculture and increased use efficiency.

Material Economics has estimated that by implementing these measures (in an ambitious scenario) the demand for ammonia in the EU could be reduced by 45% in 2050 compared to a baseline scenario that largely continues current practice (Material Economics, 2019). This reduction is based on an estimated potential to reduce food waste by 70%. In addition, it is based on the use of various techniques to improve uptake of nitrogen by plants and reduce excess nitrogen application. Finally, Material Economics assumes a switch to a larger share of organic fertilisers.

Energy efficiency improvements

Several possible energy efficiency improvements have been suggested in the literature, such as improvements in the reformer section, improvements in the carbon dioxide removal section, low pressure ammonia synthesis, improved process control and improved process integration (Overgaag, Harmsen and Schmitz, 2009) (CEFIC, 2013).

Specific measures for the Dutch fertiliser industry that have been identified by CE Delft are:

- Installing a gas turbine before the furnace, which could reduce final energy consumption by 10% (De Bruyn, Koopman, Van Lieshout, Croezen and Smit, 2014).
- Ammonia synthesis at lower pressure. In this case, less energy would be needed for compression. However, this option is only relevant for new plants.

Urea plants can undergo various revamping measures, including the use of advanced stripping technology and novel process concepts (Overgaag, Harmsen and Schmitz, 2009).

Biogas

Animal manure is an important source of methane emissions. The emissions can be substantially reduced by fermentation of the manure. The biogas that is produced can replace natural gas. Anaerobic digestion is commercially available and has a TRL level of 9 (WSP/Parsons Brinckerhoff, DNV GL, 2015).

Zitta Biogas Chemelot (ZBC) is developing a large-scale biogas plant on the Chemelot industrial site (OCI N.V., 2018a). In September 2018, ZBC has received a permit for a biogas plant with an annual input of 875 kt of animal manure²⁵ and 85 kt of cosubstrate per year. The plant is planned to produce 63 million Nm³ of uncleaned biogas, 85 kt of fertiliser pellets and 30,000 m³ of ammonium sulfate (fertiliser) per year (Gedeputeerde Staten van Limburg, 2018b). The majority of the biogas will go to OCI Nitrogen (43 million Nm³ of biogas per year). Excess biogas (19,6 million Nm³ per year) will be used by ZBC to heat air that is used to dry and pelletise the solid fraction. The heat will be produced with six new burners of 3.6 MW each (Gedeputeerde Staten van Limburg, 2018b). Next to that a significant amount of waste heat from OCI Nitrogen will be used for pre-heating. OCI has mentioned that the

²⁵ 675 kt of slurry and 200 kt of solid manure.

original plans of ZBC would require an investment in excess of EUR 80 million (De Geus, 2017).

Heat and CO₂ distribution

In 2009, Yara Sluiskil started to deliver heat and CO₂ to greenhouses in its vicinity in the WarmCO₂ project (Yara Benelux BV & Yara Tertre SA/NV, 2015). The CO₂ is used to stimulate crop growth. CO₂ can also be used in the food and beverages industry, as dry ice for cooling and for other industrial purposes (Yara Benelux BV & Yara Tertre SA/NV, 2015). Currently, Yara Sluiskil captures around approximately 1.3 million tonnes of CO₂ per year for use in the production of urea and in horticulture (Van Lieshout, Rooijers and Croezen, 2018). Highly concentrated CO₂ released at OCI Nitrogen is used for the production of urea, melamine, caprolactam and acrylonitrile. After further purification, the CO₂ is also used in the food and beverages industry and as dry ice (OCI Nitrogen B.V., 2019). These forms of utilisation of CO₂ are not considered to be emission reduction, as the CO₂ is released elsewhere at a later moment in time.

Solid state ammonia synthesis

In Solid State Ammonia Synthesis (SSAS) NH₃ is produced directly from N₂ and H₂O, without intermediate steps. Direct electrochemical ammonia synthesis in molten-salt electrolytes and on membranes are under development. This could potentially reduce electricity consumption by up to 30% (Philibert, 2017).

The TRL of solid state ammonia synthesis using electricity is 3–5 (WSP/Parsons Brinckerhoff, DNV GL, 2015). Improvements are required into the ratio of NH₃ to H₂, material durability and conditions of operation (pressure and temperature) (ISPT, 2017).

Abatement of nitrous oxide

The production of nitric acid leads to emissions of nitrous oxide (N₂O), which is a strong greenhouse gas. For the abatement of nitrous oxide, measures can be taken to remove N₂O from the process gas stream between the outlet of the ammonia oxidation and the inlet of the absorption tower. Alternatively, measures can be taken that reduce nitrous oxide after the absorption process (CEFIC, 2013).

5 Discussion

This section discusses the decarbonisation options for the fertiliser industry in terms of their feasibility and preferences of the companies.

OCI Nitrogen considers its facilities in the Netherlands a driving force in reducing the chemical industry's impact on climate change, in line with the Dutch national target to reduce greenhouse gas emissions by 49% in 2030 (OCI N.V., 2018a). From the collaboration on the 'Power to Ammonia' study (ISPT, 2017), OCI Nitrogen concludes that CO₂-neutral ammonia produced in an electrochemical way from sustainable electricity will be a feasible alternative for ammonia produced from natural gas in the longer term, but that this is not economically feasible currently (OCI N.V., 2018a). OCI Nitrogen thinks that open access hydrogen and CO₂ distribution networks can enable locations throughout the Netherlands to decarbonise.

The Vision 2025 of Chemelot stresses that big steps need to be made in the coming years to strengthen Chemelot's competitiveness and retain the employment in the region. By investing knowledge and money in energy efficiency, substitution of fossil feedstocks, increased use of waste heat, the use of renewable energy and application of CCU, the costs can be lowered and the CO₂ footprint can be reduced drastically (Chemelot, 2018).

One of the main priorities of Yara is to invest in technologies for a circular economy and to reduce emissions. The project 'Plant of the Future' looks into ways to optimise the current plants and future plants that can produce without greenhouse gas emissions. Yara believes that it will eventually be possible to produce ammonia and nitric acid from green electricity on a large scale (Yara Sluiskil B.V. , 2018). A group of companies in the Delta region (including Yara) sees the development of a future-oriented energy infrastructure for electricity and CO₂-free gas (predominantly hydrogen) as a key priority (Van Lieshout, Rooijers and Croezen, 2018).

References

- Bazzanella A and Ausfelder F. (2017). Low carbon energy and feedstock for the European chemical industry. Frankfurt am Main: DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V.
- Benner J, Van Lieshout M and Croezen H. (2011). Identifying breakthrough technologies for the production of basic chemicals; A long term view on the sustainable production of ammonia, olefins and aromatics in the European region. Delft: CE Delft.
- Boot H. (1994). Sectorstudie kunstmestindustrie. Apeldoorn: TNO Milieu- en Energietechnologie.
- CBS (2018). Bedrijfsleven; arbeids- en financiële gegevens, per branche, SBI 2008.
- CBS (2018). Standaard Bedrijfsindeling 2008 - version 2018 .
- CEFIC (2013). European chemistry for growth: Unlocking a competitive, low carbon and energy efficient future.
- Chemelot (2018). Visie Chemelot 2025:De meest competitieve en duurzame chemie en materialensite van West-Europa.
- Chemelot Site Permit B.V. (2018). Milieujaарverslag 2017.
- Chemicals Technology (2019). Yara International Urea Plant. Retrieved January 4, 2019, from <https://www.chemicals-technology.com/projects/yara-international-urea-plant/>
- De Bruyn S, Koopman M, Van Lieshout M, Croezen H and Smit M. (2014). Economische ontwikkelingen energie-intensieve sectoren. CE Delft.
- De Geus G. (2017). OCI Nitrogen; Praktische uitdagingen bij transitie energie-intensief bedrijf (Symposium EZ 16 March 2017).
- Dow Benelux (2018, July 20). Waterstofuitwisseling met Yara. Retrieved January 4, 2019, from www.dowduurzaam.nl: <http://www.dowduurzaam.nl/initiatief/waterstofuitwisseling-met-yara>.
- EBN, Gasunie (2017). Transport en opslag van CO₂ in Nederland; Verkennende studie door Gasunie en EBN in opdracht van het ministerie van Economische Zaken. Utrecht.
- Ecofys, Fraunhofer Institute for Systems and Innovation Research, Öko-Institut (2009). Methodology for the free allocation of emission allowances in the EU ETS post 2012.
- European Commission (2007). Integrated Pollution Prevention and Control Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals - Ammonia, Acids and Fertilisers. European Commission.
- European Commission (2016). The EU Emissions Trading System (ML-06-16-080-EN-N).
- Eurostat (2008). Statistical Classification of Economic Activities in the European Community, Rev. 2 (2008).
- Fertilizers Europe (2000). Best Available Techniques for Pollution Prevention and Control in the European Fertiliser Industry; Production of urea and urea ammonium nitrate. Brussels.
- Fertilizers Europe (2018). Industry facts and figures 2018.
- Gedeputeerde Staten van Limburg (2017). Besluit van Gedeputeerde Staten van Limburg, m.e.r. beoordeling, OCI Nitrogen B.V. en Chemelot Site Permit B.V. Maastricht: Gedeputeerde Staten van Limburg.
- Gedeputeerde Staten van Limburg (2018a). Omgevingsvergunning 20 september 2018 (2018/62209).
- Gedeputeerde Staten van Limburg (2018b). Omgevingsvergunning 28 september 2018 (2018/65706).
- Gedeputeerde Staten van Zeeland (1998). Omgevingsvergunning 30 januari 1998 (980973/979453).

Gedeputeerde Staten van Zeeland (2000). Veranderingsvergunning 16 mei 2000 (005041).
 Gedeputeerde Staten van Zeeland (2003). Omgevingsvergunning 9 januari 2003 (030373).
 Gedeputeerde Staten van Zeeland (2008). Omgevingsvergunning 12 augustus 2008 (08023856).
 Gedeputeerde Staten van Zeeland (2009a). Omgevingsvergunning 2009 (09038211/Wm.08.022).
 Gedeputeerde Staten van Zeeland (2009b). Omgevingsvergunning 25 maart 2009.
 Gedeputeerde Staten van Zeeland (2010). Omgevingsvergunning 28 juni 2010 (10022707/Wm.09.018).
 Gedeputeerde Staten van Zeeland (2015). Omgevingsvergunning 14 juli 2015 (W-AOV140507).
 Gedeputeerde Staten van Zeeland (2016). Omgevingsvergunning 23 mei 2016 (W-AOV150362/00108007).
 Gedeputeerde Staten van Zeeland (2017a). Omgevingsvergunning 23 januari 2017 (W-AOV160521/00147661).
 Gedeputeerde Staten van Zeeland (2017b). Omgevingsvergunning 8 september 2017 (W-AOV179318/00168424).
 Gedeputeerde Staten van Zeeland (2018). Omgevingsvergunning 1 maart 2018 (W-AOV170624/00179911).
 Hendriks C, Koornneef J and Oude Lohuis J. (2015). CCS position paper. Ecofys.
 ICL (2019). ICL Amsterdam. Retrieved January 24, 2019, from <http://www.icl-group.nl/icl-europe-2/>
 IEA (2009). Energy technology transtions for industry, Strategies for the next industrial revolution. IEA/OECD, Paris.
 IEA/OECD (2007). Tracking Industrial Energy Efficiency and CO₂ emissions.
 International Fertilizer Industry Association (IFA). (2009). Energy Efficiency and CO₂ Emissions in Ammonia Production; 2008–2009 Summary Report. Paris.
 ISPT (2017). Power to ammonia - Feasibility study for the value chains and business cases to produce CO₂-free ammonia suitable for various market applications. ISPT, Amersfoort.
 Kool A, Marinussen M and Blonk H. (2012). LCI data for the calculation tool Feedprint for greenhouse gas emissions of feed production and utilization. Blonk Consultants, Gouda.
 KPMG, TNO, ECORYS (2004). Ketenstudie ammoniak, chloor en LPG.
 Lako P. (2009). Energy conservation potential of the nitrogen fertiliser industry. ECN. Material Economics. (2019). Industrial transformation 2050- Pathways to Net-Zero Emissions from EU Heavy Industry.
 Meststoffen Nederland (2015). Productie van minerale meststoffen in Nederland.
 Morgan ER. (2013). Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind. Open Access dissertations, 697.
 Neelis M. (2008). Monitoring Industrial Energy and Carbon Flows. Thesis Utrecht University.
 OCI N.V. (2018a). Annual report 2017.
 OCI N.V. (2018b). H1 2018 Results Report.
 OCI Nitrogen (2018a). Organisatie. Retrieved 23 November 2018, from [ocinitrogen.com: https://www.ocinitrogen.com/NL/Pages/Organisatie.aspx](https://www.ocinitrogen.com/NL/Pages/Organisatie.aspx).
 OCI Nitrogen (2018b). History. Retrieved 23 November 2018, from <https://www.ocinitrogen.com/EN/Pages/History.aspx>.
 OCI Nitrogen (2018c). Ammoniak Fact Sheet. Retrieved 5 September 2018, from https://www.ocinitrogen.com: https://www.ocinitrogen.com/Media%20Library/Ammoniak_Fact_Sheet_NL.pdf.
 OCI Nitrogen (2018d). Feiten en cijfers. Retrieved 23 November 2018, from [ocinitrogen.com: https://www.ocinitrogen.com/NL/Pages/Feiten-en-Cijfers.aspx](https://www.ocinitrogen.com/NL/Pages/Feiten-en-Cijfers.aspx).
 OCI Nitrogen B.V. (2019). Carbon Dioxide. Retrieved 4 January 2019, from <https://www.ocinitrogen.com/ammonia/EN/Pages/Sustainability-Carbon-Dioxide.aspx>.

- OCI Nitrogen (2012). Production of mineral fertilisers. Retrieved May 1, 2019, from https://www.ocinitrogen.com/fertilizers/EN/Documents/Productieproces_Fertilizers%20final_V5_EN.pdf.
- OECD/IEA (2017). Energy Technology Perspectives, Catalysing Energy Technology Transformations.
- Overgaag M, Harmsen R and Schmitz A. (2009). Sectoral Emission Reduction Potentials and Economic Costs for Climate Change (SERPEC-CC); Industry & refineries sector. Ecofys, JRC-IPTS.
- Petrochem (2019). Yara - Petrochem. Retrieved 4 January 2019, from <https://www.petrochem.nl/fotograaf/yara/>.
- Philibert C. (2017). Renewable energy for industry; From green energy to green materials and fuels. OECD/IEA.
- Port of Rotterdam (2017). Nieuwsbericht 'ROAD project to be cancelled, CCS to continue' (29 June 2017).
- Rosier Nederland B.V. (2019). Welkom. Retrieved 24 January 2019, from <http://www.rosier.eu/nl/>.
- Schyns J. (2006). Towards a simple, robust and predictable EU Emissions Trading Scheme, Benchmarks from concept to practice. Utility Support Group, Geleen.
- Stork M, De Beer J, Lintmeijer N and Den Ouden B. (2018). Chemistry for Climate: Acting on the need for speed; Roadmap for the Dutch Chemical Industry towards 2050. Ecofys, Berenschot.
- Van Cappellen L, Croezen H and Rooijers F. (2019). Feasibility study into blue hydrogen; Technical, economic & sustainability analysis. CE Delft, Delft.
- Van Lieshout M, Rooijers F and Croezen H. (2018). Roadmap towards a climate neutral industry in the Delta region. CE Delft, Delft.
- Velthof G, Koeijer T, Schröder J, Timmerman M, Hooijboer A, Rozemeijer J, Van Bruggen C, and Groenendijk P. (2017). Effecten van het mestbeleid op landbouw en milieu, Beantwoording van de ex-postvragen in het kader van de evaluatie van de Meststoffenwet. Wageningen Environmental Research, Wageningen.
- Verkerke R. (2007). BBS 'Samen veilig'. Yara Sluiskil B.V.
- Vries T. (2018). CO₂ transport and storage in the Netherlands (presentatie North Sea Energy Conference). Gasunie.
- WSP/Parsons Brinckerhoff, DNV GL (2015). Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Chemicals; Appendices.
- Yara (2018a). Yara Sluiskil. Retrieved 23 November 2018, from <https://www.yara.nl/over-yara/yara-in-de-benelux/yara-sluiskil/>.
- Yara (2018b). Yara in de Benelux. Retrieved 23 November 2018, from <https://www.yara.nl/over-yara/yara-in-de-benelux/>.
- Yara (2019). Over Yara Sluiskil. Retrieved 4 January 2019, from <https://www.yara.nl/over-yara/yara-in-de-benelux/yara-sluiskil/over-yara-sluiskil/>.
- Yara Benelux BV & Yara Tertre SA/N.V. (2015). PURE NUTRIENT INFO #11. Vlaardingen.
- Yara HESQ/ JenssenTK. (2011). Calculation of Carbon Footprint of Fertilizer Production.
- Yara Sluiskil (2011). Health, Safety & Environment information Yara Sluiskil.
- Yara Sluiskil B.V. (2018). Kijk op Yara, Samen klaar voor de toekomst, Duurzaamheidsverslag 2017.
- Yara Sluiskil B.V. (2014). Kijk op Yara; Een energieke onderneming in de Kanaalzone.
- Yara Sluiskil B.V. (2017). Kijk op Yara; Voortdurend in ontwikkeling; Duurzaamheidsverslag 2016.
- Yara Sluiskil N.V. (2016). Kijk op Yara, Kansen door samenwerken, Duurzaamheidsverslag 2015.