ISPT

Institute for Sustainable Process Technology

Low carbon ammonia

Opportunities for **low carbon** ammonia in 2030

Content

1. Executive summary

1.1 Background

Fertilizers Europe has asked the Dutch Institute of Sustainable Process Industry (ISPT) to evaluate three different options for partial low carbon ammonia production, depending on technologies, energy prices and CO_2 prices in 2030. For this evaluation, the ISPT cost model has been used. The cost calculation has been done for ammonia produced in a traditional SMR plant, for a SMR plant where the CO_2 produced in the SMR process is stored (called in this report CCS) and for an existing SMR plant with an add-on electrolyser producing hydrogen in a low carbon way. The add-on electrolyser produces hydrogen to make 10% of the daily output, 150 tons, low carbon ammonia. Options like enriched natural gas or bio-based feedstock are not involved in this study.

The average age of the European ammonia plants is more than 40 years and halve of these plants have been built between 1970-1979 and hardly any new plants are foreseen. Despite their age, the European ammonia plants are on average the most energy efficient ones in the world. The investments towards efficiency have been driven by the high gas price in Europe. Increasing energy efficiency of ammonia plants automatically results in reduction of greenhouse gas emissions, but the technical limit is in sight, the potential for further improvement of existing plants is limited[1].

Looking at what direction the societal and political awareness is developing in Europe, the way forward for the ammonia industry is to implement low carbon technologies, and at the same time ask the European Union to implement legislation that will minimise carbon leakage and restrict import of ammonia and nitrogen fertilizers with higher carbon footprint.

This report is limited only to a scenario whereby the low carbon ammonia installation represents 10% of the production of an existing SMR plant. Production of a higher proportion of low carbon ammonia were not subject of this study. Neither does this study looks at the competitiveness of EU ammonia production compared with ammonia produced outside EU with lower gas prices. Looking ahead to 2050, it is worth noting that ammonia production without the use of SMR will most likely remove the carbon dioxide necessary for urea production, making nitrates much more important.

[1] Ecofys: Fertilizers and Climate Change (2015)

1.2 Key findings

1. Low carbon ammonia may provide opportunities for the ammonia industry in an increasingly carbon-constrained world. However, the opportunities only exist with sufficient availability of competitively priced electricity and adequate border protection. Under these circumstances ammonia could not only be used as a feedstock for fertilizers but there might be opportunities for ammonia as a carbon-free energy carrier and storage medium.

2. The cost price analyses have been done with the gas price, electricity price, CO_2 price and CAPEX for electrolysis and CCS for the years 2019 and 2030.
The outcome for **2019** shows that SMR is by far the most economical option compared to CCS and partial electrolysis.
    a. CCS result in higher production cost *and* CCS is not an option because the storage facilities in Europe are not available.
    b. Electrolysis is not an option because the capacity of the electrolysers is too small for the average ammonia plant *and* the electrolysers are far too expensive.

Cost analyses for 2019 Q1

Electricity price in the Netherlands EUR/MWh	€48,60
CO_2 price €22,2/ton	**SMR**

3. It is possible to produce low carbon ammonia by **2030**, thus lowering towards zero greenhouse gas emissions. But only for some combinations the electricity price and the CO2 price. The cost analysis has been done with a gas price of €28,50/MWh and weighted cost of capital (WACC) of 6%. The table below shows the economically most favourable technology for respectively SMR, SMR + CCS, and alkaline electrolysis. PEM electrolysis is another option; however, all calculations done show that with foreseeable market conditions in 2030, Alkaline will be competitive over PEM.

Cost analysis for 2030

Electricity price in EUR/MWh		€20	€30	€40	€50	€60	€70
CO_2 price	€25						
	€40	**Alkaline electro-lyser**				**SMR**	
	€75						
	€100					**SMR + CCS**	

   a. Alkaline electrolysis is financially more competitive than SMR if electricity prices are around or below €30/MWh, regardless of the CO_2 price.
   b. If the electricity price is around €40
      i. *and* the CO_2 price is around or lower than €40, SMR is financially most competitive
      ii. *and* the CO_2 price is around €75 or higher, Alkaline is financially most competitive.

c. SMR is financially most competitive if electricity prices are around or higher than €50/MWh *and* the CO_2 price is around or lower than €75 per ton.
d. CCS in combination with an existing SMR plant is only attractive when electricity prices are around or higher than €50/MWh *and* the CO_2 price is around €100 per ton.

This can be the situation in 2030 under the following conditions:

4. The CAPEX for electrolysers is foreseen to reduce substantially in the coming decade. The cost model calculates with a CAPEX of €700/kW in 2030 for alkaline. The capacity of electrolysers must increase substantially in order to strengthen the business case for low carbon ammonia.

5. Supply of large amounts of low-priced carbon-free electricity is a condition for successful implementation of 'green' electrolysis. Therefore, the capacity of wind and solar parks in Europe should multiply in the coming decade.

6. CCS is only an option in countries where the infrastructure for transportation and storage of CO_2, including pipelines or barges for transportation towards storage, is being developed.

7. The expansion of renewable energy will lead to more volatility on the electricity market. An electrolyser producing low carbon hydrogen gives an ammonia plant the option to reduce greenhouse gas emissions. Reduction of greenhouse gas emissions goes hand in hand with peak shaving, switching the electrolyser off at times of high electricity prices and thus only using 'cheap' electricity.
    a. An electrolyser can switch down (to 15%) very quickly, thus avoiding the short periods that electricity is very expensive, peak shaving. For 2030 'discount' up to 20% on the wholesale price can be obtained for 6500 full load hours (FLH) per year. This 'discount' can be obtained at the electricity wholesale market preferably at the Day Ahead market.
    b. If the electrolyser switches down the SMR has to produce more hydrogen so the volume of the ammonia synthesis is stable.
    c. Avoiding the hours with expensive electricity, thus having less operational hours, needs to be weighed against the CAPEX of the electrolyser. The fewer the operational hours, the higher the fixed cost per hour.

8. Carbon leakage or imports of low-cost ammonia from regions without carbon constraints or taxation must be avoided. This can be the case if CO_2 prices are high and there is no European import restriction.

9. Delivering peak shaving helps the stability of an energy system with a high percentage of renewable energy, and can be seen as a (paid) service of the industry to the larger energy system.

10. The ammonia industry will not be the only sector in need of affordable carbon-free electricity. Other industries, like mobility and housing, are also looking at electrification to reduce their carbon footprint. This will lead to an enormous rise in demand, and to high uncertainty regarding the availability and the price of carbon-free electricity.

11. The market potential for low carbon ammonia seems most attractive as shipping fuel and seasonal energy storage, but only if the price for low carbon ammonia will decrease and become cost competitive.

12. Investing in and gaining experience with small-scale add-on electrolysers and at the mean time observing how CCS is developing and how the world market for carbon free hydrogen is developing, is a robust strategy. This must be combined with advocacy to obtain a level playing field with ammonia and nitrogen fertilizers from areas with less carbon constraints

2. Introduction

2.1 Background

In Europe, there are 56 ammonia plants and more than 120 production sites in which mineral fertilizers are being produced. The vast majority of these plants have been in operation since more than 30 years, using natural gas as a feedstock and energy carrier. Despite their age, the European ammonia plants are on average the most energy efficient ones in the world. The investments have been driven by the high gas price in Europe. Increasing energy efficiency of ammonia plants automatically results in reduction of greenhouse gas emissions, but the potential for further improvement of existing plants is limited[2].

Some 80% of all ammonia produced worldwide is being used for fertilizers. The production of fertilizers is energy intensive and emits large quantities of CO_2. For every ton of ammonia roughly 2 tons of CO_2 are being emitted in the EU. The ammonia and fertilizer industry in Europe is using less energy than plants elsewhere and emits more than 20 Mton CO_2 per year in Europe[3]. The worldwide demand for fertilizers and thus for ammonia is expected to grow in the next decades, which means that also greenhouse gas emissions will grow, unless the industry implements technologies to reduce greenhouse gas emissions.

In its report Feeding Life 2030, Fertilizers Europe, the European industry organisation, has identified other market applications for ammonia than only as building blocks for fertilizers and for the chemical industry, and emphasizes the need for more efficient use of fertilizers and the importance of reducing the carbon footprint. The report indicates new applications for ammonia, like the storage of renewable energy on a seasonal basis, as fuel for mobility and as a hydrogen carrier. Thus, ammonia can play a larger role in a low carbon energy system.

Fertilizers Europe has asked the Dutch Institute for Sustainable Process Technology (ISPT) to execute a study of various options to produce low carbon fertilizers in 2030. This is a familiar subject for ISPT, because they have carried out a study Power to Ammonia in 2016, together with companies active in the whole value chain. In that study, the use of ammonia as a seasonal energy storage option has been explored. The Institute for Sustainable Process Technology is a platform aiming to realize a circular and carbon neutral process industry in 2050 in The Netherlands. They initiate and look for radical change which can be achieved through technological innovation and cooperation. It is an active and open innovation platform for sustainable process technology that connects stakeholders from different sectors and disciplines. Industry, SME's, scientists and governmental bodies find an inspirational and trusted environment in which they can optimally work together to stimulate break-through innovations.

This report describes the results of a quick scan to evaluate three technologies which can substantially reduce greenhouse gas emissions.

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[2] Ecofys: Fertilizers and Climate Change (2015)
[3] https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1

2.2 Focus of the study

This study analyses the technical possibilities and costs to produce low carbon ammonia in 2030 in an existing SMR ammonia plant in Europe, as an option to reduce CO_2 emissions. The economics for low carbon ammonia are the main subjects in this study. The market situation in The Netherlands has been used to calculate the economic aspects.

This study is based on the following premises:

- The study analyses the possibilities to build an electrolyser as add-on unit to an existing ammonia plant. The electrolyser produces enough hydrogen to make 150 ton of low carbon ammonia per day, which is equivalent to 10% of the output of an average ammonia plant.
- For CCS, this study focuses on the CO_2 process emissions in the SMR process.
- The production costs of ammonia have been calculated with a model that has been developed by the Dutch Institute for Sustainable Process Technology.
- The calculations have been done for an average European ammonia plant using the market conditions in The Netherlands in 2019 and a bandwidth for the expected conditions in 2030.
- CCS and electrolysis are not yet fully commercially available on an industrial scale. The CAPEX has to be diminished and the electrolyser capacity has to increase.
- The market potential for low carbon ammonia has been evaluated for four markets:
    - agriculture,
    - chemical building blocks,
    - shipping fuel and
    - energy storage.

Chapter 3 gives an overview of some important societal and political drivers as answers to the challenge of climate change. Chapter 4 gives more information about the market potential, chapter 5 describes the low carbon technologies which have been reviewed and chapter 6 gives more insight in the economics.

The study has been carried out by Hans Wiltink, in cooperation with his colleague Jan Paul van Soest (partners, De Gemeynt cooperative), with supportive input by Jan Jaap Nusselder and Ruud Swarts of OCI Nitrogen and Grupa Azoty. The report was reviewed by Tjeerd Jongsma (director, ISPT), Antoine Hoxha, Michal Wendolowski and Jacob Hansen (Fertilizers Europe). Representatives of Fertilizers Europe, OCI Nitrogen, Yara, Borealis, Fertiberia and Grupa Azoty participated in a meeting in which this subject has been discussed extensively.

3. Drivers for low carbon ammonia

This chapter gives an overview of relevant developments in Europe that influence the fertilizer industry. The current situation and future market developments in The Netherlands will be explained; these are the basis for the calculation of the production costs. This section ends with a short review of the situation in Spain and Poland.

Key drivers that can affect the industry’s R&D and investment strategies:

- The public and political awareness on climate change is increasing rapidly in the majority of the European countries. This puts more pressure on governments to adopt and implement more effective policies. Both NGO’s and young people demand more and more effective governmental actions in order to stop climate heating. These demands also translate into successful legal procedures, like the Urgenda lawsuit in The Netherlands. A Dutch NGO has called the Dutch government to court and has won its case. The implication is that the Dutch government has to speed-up its actions to reduce greenhouse gas emissions. In other countries, similar cases are being prepared.

- The financial sector, including national banks, shows an increasing interest in the risks climate change can pose for investments and the risks to the financial system in general. The Dutch national bank has published a study in 2018, concluding a CO_2 price of €50/ton has no negative effects on the general economy. However, the bank also said that this conclusion is not valid for energy intensive industries and global players. Other financials companies, like BlackRock investors, are pushing companies to pay more attention to their long-term strategy, including issues like protecting the environment, gender issues and racial inequality[4].

- The ETS price for CO_2 was €6 in May 2016, increased to €26 in May 2019 and is expected to grow to € 46,50 in 2030[5]. With this CO_2 price, the total expense for an ammonia plant is substantial.

- Due to the realisation of large wind and solar farms, there will be more supply of solar and wind power. This will change the energy mix and will change the prices, both the average commodity prices and the price volatility.

Two drivers will be elaborated in the next sections more in detail: the electricity price and the CO_2 price. The reason to have a more detailed look at these two drivers is that they have a major impact on the business cases for two technologies electrolysis and CCS.

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[4] https://www.blackrock.com/corporate/investor-relations/larry-fink-ceo-letter
[5] PBLprojectie ETS prijs (2018)

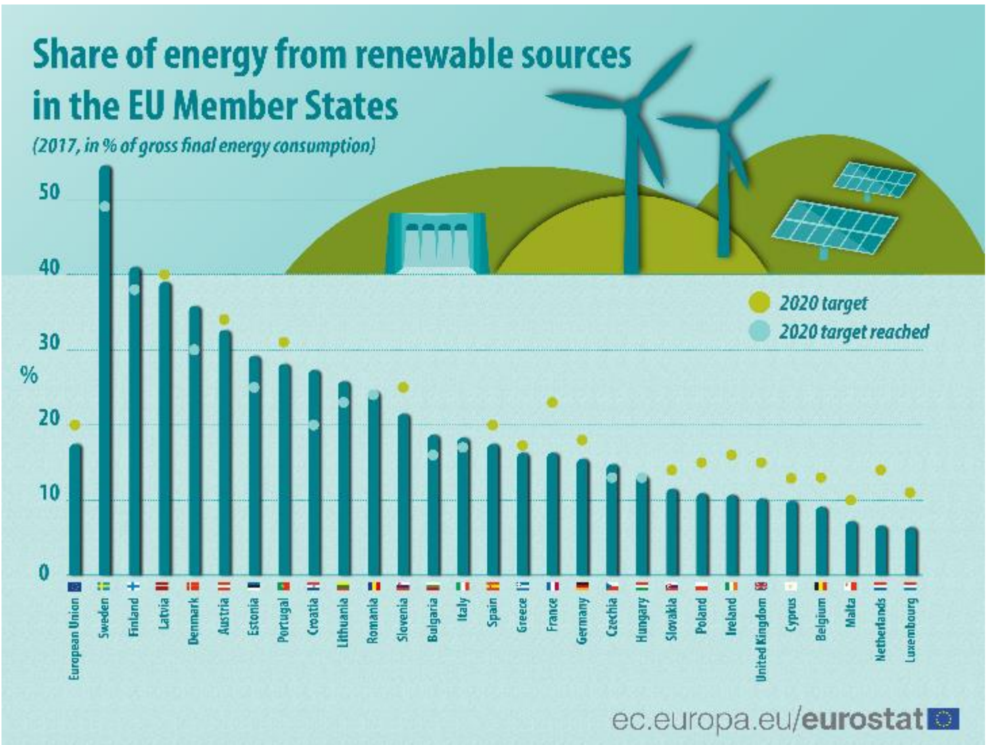
3.1 Electricity prices

European energy policies are aimed at meeting the Paris climate agreement targets. They comprise energy efficiency improvements, increasing the share of renewable energy and decarbonizing fossil fuels by promoting carbon capture and storage (CCS). The European Union has set the following targets for 2030:

- At least 40% cuts in greenhouse gas emissions (from 1990 levels)
- At least 32% share for renewable energy gross final consumption of energy
- At least 32.5% improvement in energy efficiency

All EU members have set national targets to reduce the greenhouse gas emission, among others by producing more renewable energy. The Dutch government has set up a process to realize a 'climate agreement' between governments, companies, sector organisations, NGOs and others. The preliminary results have been reviewed by independent institutes and advisory boards.

The EU target for renewable sources for 2020 is 20% of the final energy consumption. The graph shows targets and results for 2020 in all member states. Ten countries have already met their target and the rest, including Spain, Poland and The Netherland, not yet.



In order to meet the EU target for 2030, the Dutch government agreed to expand offshore wind capacity in 2030 with an additional 11.5 GW.

This expansion of renewable energy, mainly wind and solar, will have a major impact on the European energy market. The energy mix is changing, and prices will be more volatile. There will be periods with lower electricity prices when it's windy and sunny if at the same time demand is low. And there will be periods with higher electricity prices when supply is low and demand is high. Energy intensive industry, like ammonia plants, that are able and willing to switch off when electricity prices are high can get a discount on the wholesale price for a limited numbers of hours per year. This is called peak shaving. The discount in The Netherlands in 2018 was around 10% for 5000 hours per year

The main sources for carbon free electricity in Europe, besides nuclear power, are wind and sun. Subsidies, pilots, upscaling and new partnerships in the value chain have resulted in a spectacular decrease in the cost for wind. In 2018 offshore wind concessions have been granted in North West Europe without subsidies. That means that the levelized cost of energy (LCoE) became competitive with fossil-based electricity.

The table below show the levelized cost of energy (LCoE). This is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCoE can also be regarded as the average minimum price at which electricity must be sold in order to be break-even over the lifetime of the project[6]. The table gives an overview of current and predicted LCoE in The Netherlands and for solar parks in Saudi Arabia.

The Netherlands[7]	**2018**	**2030**
	€/MWh	€/MWh
Solar pv rooftops	70	40
Solar pv utility scale	80	45
Wind onshore	70	40
Wind offshore, excluding grid connection	40-50	30-40
Middle East[8]		
300 MW solar park (Sakaka) in Saudi Arabia 250 MW solar park in Dubai, late 2018.	20.50 21	

The prices for electricity in The Netherlands on the short term are fixed on the Day Ahead and the Balancing market. The Day Ahead market sets the prices per hour one day in advance, while the Balancing market defines the electricity prices for 15 minutes on the day itself. The prices fixed at the Balancing market are more volatile than the Day Ahead market, but the volume, in terms of MWh, is much smaller than the Day Ahead market.

This study analyses the economics of ammonia production in 2030 using a bandwidth between €20/MWh and €70/MWh. €20 may seem very low, but recently solar parcs in the Middle East get a permit based on the LCoE of €20/MWh and even lower. An outlook by Bloomberg[9] expects a power price for 2030 in Germany around €40/MWh. An outlook made for The Netherland by CE Delft[10] expects for 2030 a range between €30/MWh and €70/MWh. This corresponds with the used bandwidth.

[6] https://en.wikipedia.org/wiki/Cost_of_electricity_by_source
[7] Navigant: Gas for climate
[8] IRENA 2019: Renewable Energy market analysis, GCC 2019
[9] BloombergNEF: European power prices (2018)
[10] CE Delft: Energy and electricity price scenarios 2020-2023-2030 (2017)

Electrification, demand side management and the discount on the wholesale price gives the fertilizer sector an opportunity to produce low carbon ammonia and low carbon fertilizers.

3.2 ETS and the CO_2 price

The price that ammonia companies pay for emitting greenhouse gasses has increased from €6/ton in 2016 to almost €26/ton in May 2019. And the predictions are that the price will increase further. The Dutch Environmental Assessment Agency (PBL) forecasts that the CO_2 price in 2030 will be around €45/ton. The base-case EU scenario leads to a CO_2 price of almost €50 per ton CO_2 in 2030[11].

The price for CO_2 emissions under the ETS-system has a big impact on the bottom-line result of companies that emits large quantities of greenhouse gases, including ammonia plant. For an average European ammonia plant, producing 1500 ton per day, the expenses for the CO_2 emissions add up to €8 million per year at current CO_2 prices. This is calculated as follows: an average European ammonia plant emits 1.95 ton CO_2/ton NH_3. The standard capacity is 1500 ton/day, which results in annual emissions of 1.07 million tons. The free allowances for an ammonia plant are 1.33 ton CO_2 in 2019[12]. The annual cost for CO_2 emissions (price level May 2019 €25/ton) is 1.95 – 1.33 (= free allocation) x €25 x 500.000 ton/year ≈ €8 million/year.

3.3 Electricity market

The EU-target to produce 32% renewable energy in 2030 combined with the obligation to reduce greenhouse gases and higher prices for emitting $CO_{2,}$ is affecting the energy intensive industries. Not only the industry is looking for ways to use renewable energy sources, other sectors like the building sector and the mobility sector, are doing so as well. As carbon free electricity is a key solution, they are looking in the same direction: towards to suppliers of renewable electricity. The question is whether there will be enough electricity for all users, what the effect will be on the price, and what type of contracts the power sector wants pursue.

[11] Thomson Reuters The MSR: Impact on market balance and prices
[12] Benchmark (= 1.62 ton CO_2 /ton NH_3) x cross sectoral correction factor (=0.82) = Free allocation of 1.33 ton CO_2/ton NH_3

The steep rise in demand is illustrated by a CEFIC study[13] that gives an overview for the chemical industry of the demand for carbon free energy in the period to 2015 to 2050. The graph (CEFIC figure 26) shows that the demand for carbon free electricity will increase rapidly for all three scenarios (medium, ambitious and max). In two of the three scenarios ('ambitious' and 'maximum') the demand only in the chemical industry will be equal to or more than the supply in 2045 in Europe.

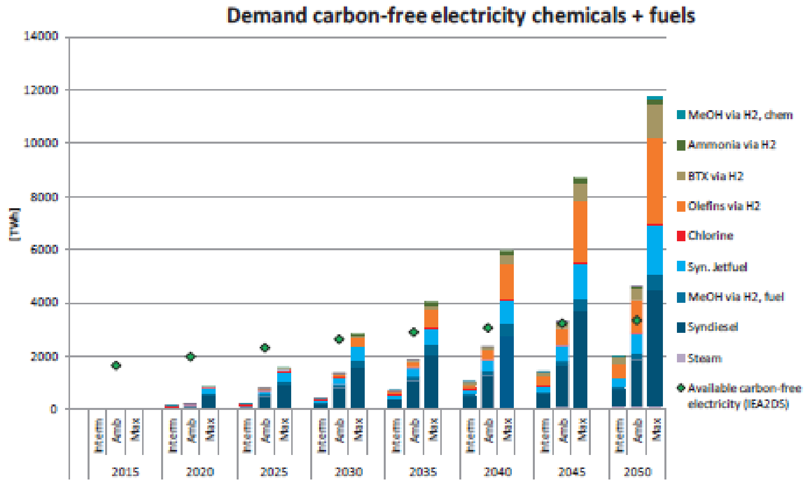


Figure 26: Carbon free electricity demand of hydrogen-based routes in all scenarios; a) chemicals only; b) chemicals and fuels The green points indicate the available carbon free electricity in Europe taken from the IEA ETP energy 2°C model;

Note that this is only the demand by the chemical industry. The demand by other sectors (other than chemical industries as well as mobility and housing) is not taken into account. The graph shows that renewable electricity supply will increase rapidly, but demand will grow even faster.

This graph shows that the availability of low-carbon power will be a critical bottleneck in the deployment of hydrogen-based chemical production technologies, like the ammonia industry producing hydrogen with electrolysers.

3.4 Country information

The expansion of renewable energy supply is foreseen in the EU. Wind and solar power are the main sources of renewable energy. That means that the electricity markets in all three countries will change due to the large share of wind and solar in the energy mix. This will have an effect on the electricity prices, that will become more volatile and the need for peak-shaving and for seasonal storage will increase. Electrolysers are suitable for peak shaving and ammonia is suitable for seasonal storage. The other route for decarbonisation is CCS. The Netherlands is working on that. Spain has no plans for CCS.

3.4.1 **Poland**

The electricity supply in Poland is mainly based on coal and lignite. Natural gas is only a very small part of the energy mix, but is increasing. There are also a growing imports of electricity and natural gas. The growth or renewable energy is stagnating. The electricity prices in Poland are high in comparison with other countries in the region. The greenhouse gas emissions, mainly caused by the energy supply sector, were more or less stable since 2000 but increased in 2017 by 4% as compared to 2016. The electricity market is exceptionally turbulent due to a law on compensations of power prices.

[13] Dechema/CEFIC: Low carbon energy and feedstock for the European chemical industry

The Draft National Energy and Climate Plan (NECP) sets no specific and quantified goals for the industry. At this moment there are no plans for an CCS infrastructure.

The target for renewable energy supply as a percentage of the final gross energy consumption is 17% in 2025 and 21% in 2030. The planned offshore renewable energy development must be ca. 5 GW by 2030 and will increase to 10 GW by 2040. The total installed net power capacity for renewable energy is planned to increase from 5 GW in 2018 to 20 GW in 2030. PV will play a large role in the expansion of renewable energy.

3.4.2 **Spain**

Spain expects that in 2030 60% of all electricity will be supplied by wind and solar, and that the wholesale price will be around €30/MWh. This is a major improvement compared to 2019 when 25% of the electricity is expected to be produced by wind and solar. The expansion of wind and solar is positive for low carbon options, because energy systems with such an amount of renewables need 1) seasonal energy storage and 2) peak shaving, reducing the electricity demand when the prices are high and vice versa. Ammonia can play a role in seasonal storage, and electrolysers are very well positioned for peak shaving. The other possible route for decarbonisation of the ammonia industry is CCS, but Spain does not have plans in that direction.

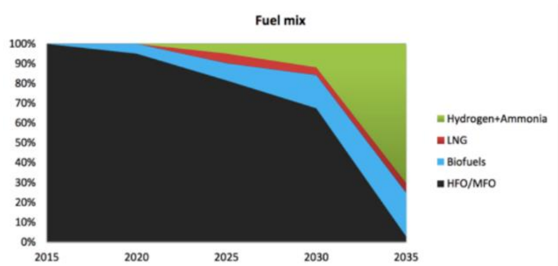
4. Market potentials for low carbon ammonia

This paragraph is based on market information in The Netherlands.

Agriculture
The products carbon footprint in agriculture is for a substantial part caused by chemical fertilizers: between 15% and 25%. Brand owners like Unilever, FrieslandCampina and LambWeston are interested in low carbon fertilizers to reduce their carbon footprint, provided that they have no price effects. They indicate that the consumer market is highly competitive, and there is only limited willingness to pay a premium for low carbon products. The fertilizers are used by the farmers, and some brand owners have no direct relationship with the farmers, so their influence on their choices is limited. Important issues for the brand owners in agriculture are climate change, soil fertility and biodiversity. One of the options is the reduction of chemical fertilizer use.

Shipping sector
For the shipping sector, in which internal combustion engines are the standard, biofuels are the most cost-effective zero-emission solution, followed by low carbon ammonia and hydrogen. Biofuels have two disadvantages: sustainability issues and limited availability. Ammonia is more competitive than hydrogen. The advantages of ammonia are lower capital costs and better options for onboard storage[14]. Another study emphasizes the higher costs and larger risks of onboard storage of ammonia as compared to hydrogen. This study says that ammonia is more costly, is highly toxic and its transport via pipelines is dangerous. There is doubt of any contribution of ammonia towards the decarbonisation of the shipping sector[15].

If ammonia will be the low carbon alternative fuel for the shipping sector, the market potential in 2030 is enormous. There are estimates that up to 10% of total demand in 2030 in this sector might be low carbon ammonia[16].
This demand corresponds with 140 kton/day[17]. The demand for low carbon ammonia as shipping fuel could further increase after 2030, as the graph shows.



Energy sector
The market potential for ammonia as an energy storage medium is uncertain at this point, and it will take at least another 5 years before 'the winner' for storage options will show up. Energy companies tell in the future renewables-based energy system, storage and carbon-free dispatchable energy will be essential, but the most competitive technologies and energy carriers are yet unknown.

[14] Lloyds: Zero-emission vessels 2030
[15] Navigant: Gas for Climate. The optimal role for gas in a net-zero emissions energy system (2019)
[16] Trevor Brown – presentation in IFA Technical Symposium, Madrid 2018
[17] IFA global technical symposium Innovations in NH_3 (2018)

Ammonia is for sure an option for seasonable storage of wind and solar energy, and has several advantages. The cost is relatively low, the energy density is high, it's easy to liquefy, it can be stored at ambient temperature and there is already a worldwide infrastructure.
An indicative scenario study done by one of the Dutch energy providers shows that the maximum seasonal storage capacity might be something between 3 and 8 million m^3 ammonia on a yearly basis. Whether ammonia will be used as energy storage medium will depend heavily on the cost for energy storage, which is currently too high. The round trip efficiency of ammonia as an energy carrier must increase to lower overall cost.

Chemical industry
Ammonia is used as raw material in the chemical industry. There is a number of options for CO_2 savings in the chemical industry, like ammonia using hydrogen from low-carbon electricity, and production of methanol, olefins and BTX (aromatics) from hydrogen and carbon dioxide. The main hurdle is the higher production cost for these building blocks. Production costs for ammonia, methanol, olefins and BTX are two to five times higher than their fossil alternatives at current conditions[18].

The similarity between these four markets is that there is a need for low carbon ammonia in the medium term, under the condition that it will become price competitive with fossil based fuels. It will take another 5 to 10 years before these markets expect this to happen.

The next chapter will elaborate in what way electrolysis and CCS can contribute to produce low carbon ammonia.

[18] Dechema/CEFIC: low carbon feedstock for the European chemical industry

5. Low carbon ammonia technologies

The EU-targets (see chapter 3.1) require fundamental innovations in the European ammonia and fertilizer industry, because the energy efficiency of ammonia production in Europe is close to the technological limit[19] and the space for further energy efficiency in an existing plant is very limited. This study looks at two options to produce low carbon ammonia which are compared to the reference case a traditional SMR plant:
1) SMR in combination with CO_2 storage (CCS), and
2) electrolysis.

5.1 SMR + CCS.

In this scenario, the process emissions in the SMR as a part of an existing ammonia plant in Europe are captured and stored (CCS). Because part of the CO_2 is already captured in the SMR part of the process, the only additional investment is in compression. Besides that, there are costs for transport and storage of the CO_2. If the total investment costs for compression and CO_2 transport and storage in a North Sea gas field amount, the cost for CCS are as follows:

- Storing the process emissions of the SMR adds up to €75/ton CO_2
- In case the remaining 1/3 of the CO_2 emitted as a flue gas of ammonia synthesis is also captured, the cost for this CO_2 flow adds up to some €200/ton CO_2.

CCS is only possible if there is enough storage capacity nearby, and if there is an infrastructure for CCS. The Dutch government has the ambition to store 7-10 Mton per year in 2030 in the North Sea. CCS in the North Sea will cost around €70-€100/ton CO_2 in 2030. Port of Rotterdam is working on a pilot for the CCS-infrastructure.

CO_2 is the by-product of ammonia production, which makes the ammonia industry a potential source for CCS. The CEFIC roadmap 'European chemistry for growth' identified not only ammonia but also crackers and combustion in general as potential sources for CCS.

The technology for CCS is already applied worldwide and the Technology Readiness Level (TRL) is 9.

CCS of process emissions reduces the CO_2 emission per ton of ammonia by 2/3.

Thus a 1500 TPD SMR plant would produce 1000 TPD low carbon ammonia.

[19] Fertilizers Europe

5.2 Electrolysis.

In this option, the hydrogen is produced by electrolyzing water instead of steam methane reforming (SMR), and the nitrogen is provided by an air separation unit (ASU) for further processing in the Haber-Bosch plant[20].

This study analyses an electrolyser as an add-on unit to an existing ammonia plant with the capacity to produce enough hydrogen for 10% of an output equivalent to 150 ton low carbon ammonia per day.

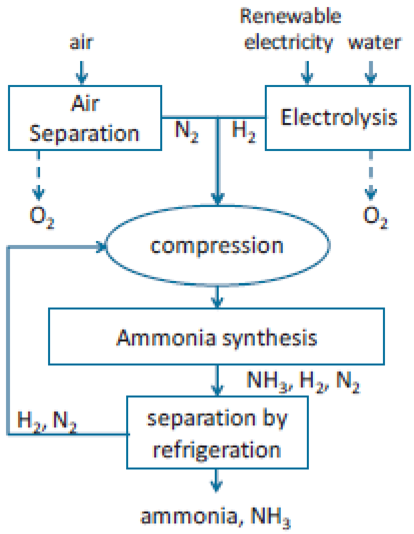


Figure 6: Scheme of low-carbon ammonia synthesis

Electrolysis is a mature technology being used in various industries, but not applicable at an ammonia plant at an industrial scale. This is the case both for alkaline and PEM, two technologies under development for large scale hydrogen production. The individual technologies are available, system integration should be straightforward, combination of electrolysis with ammonia synthesis is not at commercial stage and a certain level of heat integration will be lost in such a setup. The total energy demand is 12.5 MWh or 45.1 GJ per ton of ammonia. This carbon free route provides 4.3 GJ/t NH_3 less steam, which then has to be provided otherwise.

For this option it is important to have sufficient renewable electricity. The production of 150 ton low carbon ammonia in an add-on unit at an existing plant requires an electrolyser with a capacity of around 70 MW_e, based on 8000 full load hours (FLH) per year. If 10% of the regular output of an ammonia plant is produced with electrolysis, the plant needs a wind farm with 18 offshore wind turbines with a capacity of 8 MW_e each. For an offshore wind turbine, 50% of the installed capacity can be calculated as average yearly output. This type of electrolyser needs no specific contract for the electricity.

The big advantage of an electrolyser is that it can reduce its capacity in a very short time to a minimum capacity of 15% for alkaline and 5% for PEM. This makes the electrolyser suitable for peak shaving and avoiding the need for expensive electricity in peak hours. Avoiding the hours with expensive electricity and thus less operational hours has to be weighed against the CAPEX of the electrolyser. The fewer the operational hours, the higher the fixed cost per hour.

An operational perspective. An ammonia plant where an add-on electrolyser supplies 10% of the hydrogen results in a SMR which supplies 10% less so the volume of the ammonia synthesis is stable. In this study the electrolyser is in operation during the 6500 ‘cheap’ hours per year. If the electrolyser is turned down the SMR produces the hydrogen. The operation of the electrolyser is defined by the electricity prices fixed on the Day Ahead market which means that the plant knows one day in advance during which hours on the next day the electrolyser is turned down and the SMR has to take it over.
Another option is to act in relation to the prices fixed on the Balancing market. In that case the operation of the electrolyser, the SMR and the ammonia synthesis must be so flexible that is can turn down or up in minutes.

[20] Dechema: Low carbon energy and feedstock for the European chemical industry (2017)

Alkaline is a mature technology but not available on a large industrial scale. The TRL is in the range of 7 to 9. PEM is less mature and has TRL 7 to 8.

This technology reduces the CO_2 emission per ton of ammonia by 90%.

The table gives an overview projected in 2030 of the most relevant parameters for PEM, Alkaline and CCS, with an electricity price of €40/MWh and a gas price of €28.50/MWh[21]

	PEM	Alkaline	SMR + CCS
CO_2 reduction	90%	90%	67%
Abatement cost[22] per ton CO_2 (ISPT model)	€82	€70	€79
TRL	7-8	9 Alkaline is a mature technology. 7 for innovations	9
Electrolyzer capacity FLH 6500	85 MW_e	85 MW_e	
CAPEX 2030 in euro's	73 million	60 million	
CAPEX 2017 in euro's per kW[23]	2000-2400	1000-1200	
CAPEX 2030 in euro's per kW[24]	850	700	
Max. installed capacity in 2020	10 MW (Shell)	200 MW	

[21] IHS
[22] https://en.wikipedia.org/wiki/Marginal_abatement_cost: Abatement cost is the cost of reducing environmental negatives such as pollution.
[23] Dechema: Low carbon energy and feedstock for the European chemical industry (2017)
[24] ISPT project

6. Economics of low carbon ammonia plants

This chapter shows the results of the cost price analyses, calculated with a model developed by the Institute for Sustainable Process Technology. This model calculates the cost per ton of hydrogen and the CO_2 abatement cost, based on input data like CAPEX, OPEX, full load hours, depreciation, electricity price, gas price and other data for SMR, SMR plus CCS, Alkaline and PEM.

In this section we make a comparison between the production cost per ton of ammonia in a traditional SMR plant, in a SMR plant where the CO_2 is stored (SMR + CCS) and a plant where an add-on electrolyser unit produces enough hydrogen to produce 10% of the total capacity of an average ammonia plant as low carbon. This yields 150 ton low carbon ammonia per day.

This paragraph starts with the state of affairs of electrolysis and CCS in 2019, and shows some scenarios for 2030, including cost price analyses.

6.1 Low carbon ammonia in 2019

For 2019 Q1 the following numbers have been used. Because an alkaline electrolyser is economically more feasible than PEM, we concentrate on alkaline.

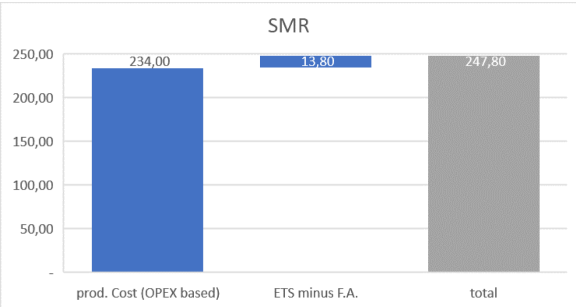
CAPEX alkaline	€1400/kW	The CAPEX for an alkaline electrolyser is currently around €1400/kW. This includes the electrolyser and the cost for retrofitting the plant.
CAPEX CCS	€110 million	The investment for the installation to compress and store the CO_2 emitted in the SMR part of the plant
FLH	8000	A discount of 10% on the wholesale price for peak shaving resulting in 5000 FLH is less attractive than 8000 FLH and no discount.
Electricity wholesale price	€48.60/MWh	The average wholesale price in The Netherlands in 2019 Q1
Gas	€18.42/MWh	Average gas price 2019 Q1 in The Netherlands
CO_2 price	€22.2/ton	Average CO_2 price 2019 Q1
Free allocation	1.33 ton CO_2/ton NH_3	

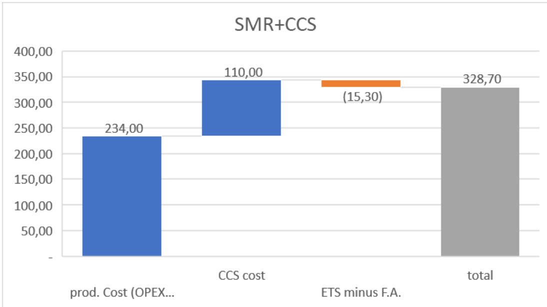
Based on these numbers, the model calculates the production cost for ammonia. Producing hydrogen with an electrolyser or storing the CO2 makes low carbon ammonia more expensive than ammonia produced in a SMR plant.

- CCS increases the production cost per ton of ammonia roughly with €110.
- An alkaline electrolyser increases the cost per ton of ammonia with almost €430.

These numbers are the numbers for the additional production costs and are not the final cost differences per ton of ammonia produced in a SMR plant, CCS and Alkaline. The final cost difference is smaller due to the following: an SMR plant has to buy CO_2 credits, and a CCS and alkaline plant can sell the free allowances they do not emit. This will make the production cost gap smaller.

The calculation of the differences in production costs for the 3 alternatives is explained with the help of the figures below. These figures show the difference in total production cost for one ton of ammonia in a SMR plant (left) and in a SMR plant with CCS (right). The starting point is €234 for the production cost on one ton ammonia[25].





An SMR plant emits per ton of ammonia 1.95 ton CO_2. The expenses in 2019 were €43.30. An ammonia plant receives 1.33 ton CO2/ton ammonia as free allocation. The value is €29.50 per ton ammonia. ETS minus F.A. = €13.80
The total production cost is €234 + €13.80 = €247.80.

The production cost per ton of ammonia in an SMR plant with CCS are €110 higher in respect off a SMR plant without CCS. The revenue of the sale of not used free allocation is €15,30 per ton ammonia.

The total production cost is €234 + €110 - €15.30 = €328.70.

One ton of ammonia produced in a SMR plant with CCS is €328.70 - €247.80 = €80.90 more expensive than a SMR plant. The calculation is done with the numbers for 2019 Q1.

The table below gives the cost figures for the production cost per ton of ammonia in the current situation, 2019 Q1.

	SMR	SMR + CCS	Alkaline
Production cost ton H_2	€1181	€1509	€3609
Additional production cost per ton of ammonia		€110	€428
Minus the expenses for CO_2 for the SMR plant	€13.80		
Minus the revenues by the sale of CO_2 credits		€15.30	€25.30
Total additional cost per ton of NH_3 including CO_2 cost and revenue sale CO_2 credits		€81	€389

In 2019, producing a ton of ammonia with an alkaline electrolyser is far more expensive than SMR and SMR combined with CCS, due to the higher cost for electricity in respect of natural gas and the high CAPEX. The additional cost, including the cost for CO_2 and revenue of the sale of CO_2 credits is €389.

[25] Fertilizers Europe

Note: PEM is not taken into account because in comparison with alkaline it has a lower TRL, a higher CAPEX which results in higher cost per ton of ammonia.

6.2 Low carbon ammonia in 2030

The calculation for 2019 has also been done with the numbers for 2030. Participants at the ISPT hydrogen project agreed on the numbers. Before we explain the production cost for 2030, we have a look at the most important cost drivers of low carbon ammonia estimated for 2030.

- **CAPEX alkaline electrolyser**. Worldwide, hydrogen is seen as one of the most promising low carbon energy carriers. In 2019, electrolysers for carbon free hydrogen are too expensive and have limited capacity. Consortia and companies all over the world are working hard on these topics. A consortium of Dutch industries led by the ISPT, has the ambition to realise a 1GW electrolyser in the Netherland in 2030. Participants in this consortium expect that the CAPEX for an 85 MW_e alkaline electrolyser, necessary to produce 10% low carbon ammonia in 2030, will be around €700/kW in 2030.

- **Electricity prices**. Europe is aiming at 32% of the final energy consumption being produced by renewables sources like wind and solar. This will not only influence the price of electricity but will also influence the correlation between the prices of natural gas and electricity. In our calculation we used an electricity price range of €20 to €70 per MWh.

- **Discount electricity**. The output of renewable energy is variable and that affects the electricity price. The volatility will increase. During a limited number of hours electricity will be very expensive and on other moment also very cheap or even available at negative prices. If plants are able to implement peak shaving and turn off when the electricity prices are high, they can obtain a discount on the wholesale price. In 2018 this discount was around 10%, in combination with FLH of 5000 hours per year. For 2030, a discount of 20% for 6500 hours per year is, according to some expert, realistic.

- **ETS**. The price for CO_2 has increased substantially in the last three years. In 2016, it was €6 per ton and in May 2019 it has reached €25.80. This study calculates with a CO_2 price in the range €25 to €100 per ton.

- **Free allowances**. The free allowance for ammonia plants in 2019 is 1.33 ton CO_2/ton of NH_3. The EU has decided that the energy intensive industries will receive a share of their emission allowances for free until 2020 and beyond. This allocation is based on benchmarks that reward most energy efficient installations in each sector. The free allocation for each installation is calculated using benchmarks developed for each product, as far as possible[26]. For 2030 we calculate with a benchmark of 1.55 ton CO_2/ton NH_3 and a CSCF of 0.8. This results in 1.24 ton free allocation.

- **CO_2 emissions**. An ammonia plant that captures and stores all CO_2 produced as process emissions in the SMR, can reduce its emissions by 2/3. In case an electrolyser is used, the reduction is around 90%. An average European ammonia plant emits 1.95 ton of CO_2/ton

[26] https://ec.europa.eu/clima/policies/ets/allowances/industrial_en

of NH_3 and is allowed to emit 1.33 ton. The difference between 1.95 and 1.33 is 0.62 ton, which must be bought. Any ammonia plant that emits less than the free allowance can sell the free allowances and receives extra revenues. This is the situation for both CCS and alkaline. This may sound strange, but it's exactly what the ETS system is aiming at. Buying and selling emission rights stimulates the industry to reduce greenhouse gas emissions in the most cost-effective ways.

The table below gives an overview of the most relevant data for 2019 and 2030 used in the calculation model.

	2019	2030
CAPEX alkaline per kW	€1400	€700
CAPEX CCS	€110 million	€110 million
Electricity price per MWh	€48.60	€20, €30, €40, €50, €60 and €70
Gas price per MWh	€18.42	€28.50
CO_2 price per ton	€22.2	€25, €40, €75 or €100
Free allocation	1.33 ton CO_2/ton NH_3	1.24 ton CO_2/ton NH_3
FLH Alkaline	8000	6500
Discount in relation to the FLH	10% and FLH 5000	20% and FLH 6500
CO_2 reduction SMR + CCS in respect of SMR	67%	67%
CO_2 reduction alkaline in respect of SMR	90%	90%

6.3 Production costs ammonia in 2030

The calculation of the production costs is done with the numbers presented in the table above. There are two variables: six different electricity prices and four different CO_2 prices. The combination of four different prices for electricity and for CO_2 results in 24 possible combinations. For every combination there is one technology with the lowest additional cost as compared to an SMR ammonia plant. For a number of combinations alkaline and CCS are cheaper than SMR. The lowest additional cost is calculated as follows (see also 6.1): the additional production cost for CCS or alkaline minus the CO_2 cost for a SMR plant minus the revenues from the sale of free allocations not used in the scenario with CCS and alkaline.

The table below shows the technology with the lowest production cost compared with SMR. The number in every cell indicates the difference in total production cost per ton NH_3 between the cheapest technology and the next cheapest option. Note that these are not the numbers for the absolute production cost.

Explanation of the table: if the price of electricity in 2030 is €40/MWh and the CO_2 price is €40, SMR is per ton of ammonia €36 cheaper than ammonia produced with electrolysis. .

electricity price in EUR/MWh		€20	€30	€40	€50	€60	€70
CO_2 price	€25	€83	€10	€62	€74	€77	€80
	€40	€109	€36	€36	€55	€58	€61
	€75	€170	€97	€25	€9	€12	€15
	€100	€215	€142	€70	€24	€21	€18

	SMR	(orange)
	SMR + CCS	(blue)
	Alkaline electrolyser	(green)

The table shows the following:

- If the electricity price is around or lower than €30/MWh, electrolysis is economically the most attractive option regardless the price for CO_2.
- If the electricity price is around €40/MWh, the outcome depends on the CO_2 price.
  - If the CO_2 price is around or lower than €40, SMR is most profitable.
  - If the CO_2 price is around or higher than €75, electrolysis is most profitable.
- If the electricity price is around or above €50/MWh *and* the CO_2 price is around or lower than €75 per ton, SMR is most attractive.
- If the electricity price is around or above €50/MWh *and* the CO_2 price is around €100, SMR + CCS is the more attractive option.

The cost price analyses show that the combination of high electricity and low CO_2 prices leads to a positive margin for SMR, up to +€80/ton NH_3. Low electricity prices lead to a large positive margin for electrolysis up to €200/ton NH_3. High electricity prices *and* high CO_2 prices leads to a small positive margin for CCS of around +€20/ton NH_3.

The cost price calculations are done with numbers for the year 2030. The positive results for electrolysis depend heavily on:
1) the speed with which electrolysis will become cheaper and upscaling is realised,
2) the realisation of ambitious plans for wind and solar parcs, so the supply of sufficient low-cost carbon free electricity is guaranteed.

Appendix

Abbreviations

CCS	Carbon capture and storage
ISPT	Institute for sustainable process technology, based in The Netherlands.
CAPEX	Capital expenditure
OPEX	Operational expenditure
MWh	Megawatt hour
kW	Kilowatt
FLH	Full load hours
SME	Small and medium enterprise
ETS	Emissions trading system
GW	Giga watt
LCoE	Levelized cost of energy
TRL	Technology readiness level.

This appendix gives an overview of the ISPT cost model.

Electrolysis

> The discount in 2018 in The Netherlands (afslag) for windenergy resulted in a discount of around 10% for 5000 windhours. In line with the discount in 2018 seams a discount of 20% and 6500 hours/yr reasonable.

Energy Carrier Prices		
Gas	0,0285	€/kwh
Electricity	0,04	€/kwh
Electricity for electrolyzer	0,032	€/kwh
Steam	20	€/t
Oxygen	27	€/t

Financial Parameters	
$/€	1,18
WACC	0,06

Energy Carrier Properties		
CO2 el	0	kg CO2/MWh
NG	46,5	MJ/kg
H2 (LHV)	33,39	kwh/kg
H2 (HHV)	39,41	kwh/kg
H2 (SMR)	8,49	kg CO2/kg H2

Project: Electrolysis (2a & 2b)
Goal: Achieve scaling (effects) with electrolysis
Year: 2030
H2 grade: 99,90% + 20 bar

We compare various zero and low carbon hydrogen production methods techno-economically, scaled to a 1 MT total capacity. Since the hydrogen produced is to be used in the chemical industry, it should have a high purity. As such this excludes certain recently produced studies (eg Berenschot, 2017). We compare PEM and alkaline electrolysis, both of which are zero carbon when the electricity used to power them is zero carbon, and the low carbon options of steam methane reforming (SMR) and auto thermal reforming (ATR, a combination of SMR and partial oxidation, POX). For the latter two options, only a limited quantity of CO2 can be captured, with SMR being most limited.

PEM Electrolysis, Alkaline Electrolysis and ATR + CCS all follow green field approaches; SMR+ CCS, however, concerns the addition of CCS to

	Tech	SMR (REF)	PEM Electrolysis	Alkaline El	SMR + CCS	ATR + CCS	
	Approach		Green field	Green field	Add CCS to REF	Green field	
Technical & Investment	Efficiency (LHV)	0,72	0,64	0,64		0,72	
	Efficiency (HHV)	0,85	0,76	0,76		0,85	
			PEM Electrolysis	Alkaline El			
	Equipment €/kW	338,98	500,00	350,00			€/kW
	Installation €/kW	0,00	350,00	350,00			€/kW
	Lifetime stack		82500,00	82500,00			hrs
	Lifetime stack		12,69	12,69			yrs
	Lifetime rest		30,00	30,00			yrs
	Fraction for stack		0,15	0,15			
	Levelised investment		952,27	771,59			€/kW
	Total Lifetime	40,00	30,00	30,00	25,00	25,00	y
	FLH	8000,00	6500,00	6500,00	8000,00	8000,00	hrs
	Peak factor	1,00	1,00	1,00	1,00	1,00	
	Capacity		0,80	0,80			Gwe
Utility	Electricity	0,57	52,17	52,17	1,65	1,19	kWh/kg H2
	Gas	45,78	0,00	0,00	0,00	45,18	kWh/kg H2
	Steam	0,00	0,00	0,00	0,00		kg
	Oxygen	0,00	-7,94	-7,94	0,00	0,00	kg
	Energy cost	1327,51	1669,50	1669,50	65,88	1335,07	€/t H2
	H2 required	0,10	0,10	0,10	0,10	0,10	Mt H2/y
	Electricity req	0,06	5,22	5,22	0,16	0,12	TWh
	Gas required	4,58	0,00	0,00	0,00	4,52	TWh
Fixed cost	Investment		0,76	0,62	0,11	0,32	B€
	Wacc	0,06	0,06	0,06	0,06	0,06	
	Wacc contribution	0,47	1,38	1,11	0,16	0,47	B€
	Investment incl wacc	0,47	2,14	1,73	0,27	0,79	B€
	Investment incl wacc	116,39	713,38	578,03	109,80	315,36	€/t H2
	O&M cost	5,00	3,00	3,00	5,00	5,00	% CAPEX
	O&M cost	232,78	229,30	185,79	137,25	394,20	€/t H2
	Equipment ETM cost	349,18	942,68	763,82	247,05	709,56	€/t H2
Revenue	Oxygen produced		0,79	0,79			Mt O2/y
	Oxygen sold		0,79	0,79			Mt O2/y
	Oxygen revenue		21,43	21,43			M€/y
	Flexcapacity value		75,00	50,00			k€/MW/y
	Flexcapacity used		0,00	0,00			GW/y
	Flexcapacity revenue		0,00	0,00			M€/y
	Share gas usage for heatin	0,30					
	Heat for hot oil + steam	0,18					TWh/y
	Reduction gas usage	0,21					TWh/y
	Actual reduction gas usage	0,21					TWh/y
	Reduction H2 cost	59,87	214,29	214,29			€/t H2
Total	Total H2 costs	1616,82	2397,90	2219,03	1929,75	2044,63	€/t H2
CO2	CO2 emissions	8,49	0,00	0,00	3,00	0,64	Mt CO2/Mt H2 emitted
		0,85	0,00	0,00	0,30	0,06	Mt CO2 emitted
	Emissions captured				5,49	0,76	Mt CO2 to be stored
	Transport & Storage cost				25,00	25,00	€/t CO2
	CO2 abatement (rel to REF)		92,00	70,93	82,00	79,47	€/t CO2

Cost comparison grey, green and blue ammonia

Energy Carrier Prices		
Gas	0,0285	€/kwh
Electricity	0,04	€/kwh
Electricity for electrolyzer	0,032	€/kwh
Steam	20	€/t
Oxygen	27	€/t

Extra cost per ton NH_3					
		SMR (REF)	**SMR + CCS**	**PEM**	**Alkaline**
			Add CCS to REF	Green field	Green field
CAPEX equipment	EUR/kW			€ 500	€ 350
CAPEX installation	EUR/kW			€ 350	€ 350
capacity needed for 150 ton NH3, 8000 hrs/yr	MWe			70	70
capacity needed for 150 ton NH3, 6500 hrs/yr	MWe			86	86
total capex 150 ton NH_3				€ 73.230.769	€ 60.307.692
FLH	hours/yr	8.000	8000	6500	6500
Energy cost	EUR/ton H_2	€ 1.328	€ 66	€ 1.670	€ 1.670
H_2 costs ex CAPEX	EUR/ton H_2	€ 1.617			
H_2 costs incl. CAPEX			€ 1.930	€ 2.398	€ 2.219
ton H_2 per ton NH_3	0,18				
aditional cost in relation to SMR	EUR/ton NH_3		€ 55,22	€ 137,84	€ 106,27

CO_2 cost				
		2020	**2030**	**2030**
CO_2 emissions standard ammonia factory	CO2 ton/ton NH3	1,95		
Benchmark EU 2020, assumption for 2030	CO2 ton/ton NH3	1,619	1,55	1,55
Cross sectorial correction factor, assumption for 2030		0,82	1,0	0,90
free allocation	CO2 ton/ton NH3	1,33	1,55	1,40
CO_2 cost per ton ammonia including free allocation	€ 25	€ 15	€ 10	€ 14
	€ 40	€ 25	€ 16	€ 22
	€ 75	€ 46	€ 30	€ 42
	€ 100	€ 62	€ 40	€ 56

based on the free allocation year 2030, CSCF 0,8, benchmark 1,55

Most cost effective option in 2030: SMR, CCS or Alkaline including sale EUA's

electricity price in EUR/MWh		€ 20	€ 30	€ 40	€ 50	€ 60	€ 70
CO2 price	€ 25	Alk. (39+18+26=€83)	Alk. (34-18-26=€10)	SMR (106-18-26=€62)	SMR (107-18-15=€74)	SMR (110-18-15=€77)	SMR (113-18-15=€80)
	€ 40	Alk. (39+28+42=€109)	Alk. (34-28-42=€36)	SMR (106-28-42=€36)	SMR (107-28-24=€55)	SMR (110-28-24=€58)	SMR (113-28-24=€61)
	€ 75	Alk. (39+53+78=€170)	Alk. (34-53-78=€97)	Alk. (106-53-78=€25)	SMR (107-53-45=€9)	SMR (110-53-45=€12)	SMR (113-53-45=€15)
	€ 100	Alk. (39+71+105=€215)	Alk. (34-71-105=€142)	Alk. (106-71-105=€70)	CCS (107-71-60=€24)	CCS (110-71-60=€21)	CCCS (113-71-60=€18)

1) The table above shows the economic most favourable option out of SMR, SMR + CCS and Alkaline. For electrolysis Alkaline is more favourable than PEM.
2) The 'best' option is choosen based on the comparison for the production cost for a ton of NH3, the cost for CO2 emissions per ton NH3, and the revenues from selling the not used CO2 credits for CCS and Alkaline. This is done for 4 different CO2 prices and 6 different electricity prices.
3) The starting point is the additional production cost for hydrogen in case of CCS and Alkaline in respect of SMR; called the cost difference. The CO2 cost which have to be paid per ton of NH3 produced in a SMR plant are substracted from the cost difference and the revenues from selling the CO2 credits for electrolysis and CCS are substracted in the same way. The numbers in between the brackets show this calculation for SMR in respect of either Alkaline or CCS, which ever is cheapest.

The 'yellow' cell is most attractive in respect of SMR.
The addtional costs per ton of NH3 are the outcome of the ISPT model. The input data can be found in the box below.
The production cost for hydrogen can be found on the page 'Hydrogen'.
Te additional cost for SMR+CCS, Alkaline and PEM in respect of SMR can be found on page 'NH3cost'.

Data used in the cost model for 2030

FLH SMR	8.000	hours
FLH Alkaline/PEM	6.500	hours
Discount peak shaving Alkaline/PEM	20%	
wholesale price electricity	€20, €30, €40, €50, €60, €70	
CO2 prices	€25, €40, €75, €100	
WACC - weighted average cost of capital	6%	
gas price	€ 28,5	per MWh
Cost CO2 storage	€ 25	per ton CO2
CAPEX PEM	€ 850	per KW
CAPEX Alkaline	€ 700	per KW
CAPEX CCS SMR plant	€ 110.000.000	
CO_2 emissions SMR plant	1,95	ton CO2/ton NH3
Benchmark EU 2019	1,619	ton CO2/ton NH3
Cross sectorial correction factor 2019	0,824	
free allocation 2019	1,33	ton CO2/ton NH3
Benchmark EU 2030	1,55	ton CO2/ton NH3
Cross sectorial correction factor 2030	0,80	
free allocation 2030	1,24	ton CO2/ton NH3

CO2 cost per ton NH3 SMR plant including free allocation

		2019	2030
benchmark		1,619	1,55
CSCF		0,82	0,80
free allocation		1,33	1,24
CO2 price	€ 25	€ 15	€ 18
	€ 40	€ 25	€ 28
	€ 75	€ 46	€ 53
	€ 100	€ 62	€ 71

additional cost per ton NH3 in respect of SMR

electr price EUR/MWh	€ 20	€ 30	€ 40	€ 50	€ 60	€ 70
CCS	€ 98	€ 101	€ 104	€ 107	€ 110	€ 113
Alkaline	€ -39	€ 34	€ 106	€ 179	€ 252	€ 324
PEM	€ -7	€ 65	€ 138	€ 210	€ 283	€ 356

Scenario 2030		Revenu sale CO2 credits/ton NH3	
		CCS	Alkaline/PEM
CO2 reduction		67%	90%
emissions/ton NH3		0,64	0,20
for sale i.r.o. free allocation	1,24	0,60	1,05
Cost CO2 per ton NH3	€ 25	€ 15	€ 26
	€ 40	€ 24	€ 42
	€ 75	€ 45	€ 78
	€ 100	€ 60	€ 105