ISPT

Institute for Sustainable
Process Technology

Power to Ammonia

Feasibility study for the value chains and business cases to produce CO_2-free ammonia suitable for various market applications

Project title: Power to Ammonia
Reference number: TESI115001

The project has been carried out with Topsector Energy subsidy of the Ministry of Economic Affairs in the period from January 2016 to February 2017

The consortium consisted of Nuon, Stedin, OCI Nitrogen, CE Delft, Proton Ventures, TU Delft, TU Twente, AkzoNobel, ECN and ISPT as coordinator

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Executive summary

Project
The Institute for Sustainable Process Technology (ISPT) has brought together various parties from different sectors of industry to study the storage of electricity in ammonia (NH_3). Objective of this power-to-ammonia (P2A) study is to investigate under what conditions 1) NH_3 can be produced using renewable electricity, 2) NH_3 can be used to store electricity and 3) NH_3 can be used as a CO_2-neutral fuel for a power plant.

P2A is a partnership of ISPT, Stedin Infradiensten, Nuon, ECN, Technical University Delft, University Twente, Proton Ventures, OCI Nitrogen, CE Delft and AkzoNobel. This project has been carried out with Topsector Energy subsidy of the Ministry of Economic Affairs for conducting the power-to-ammonia feasibility study.

Background
The electricity system is rapidly transforming towards a low carbon system, driven by ambitious CO_2-reduction targets, decreasing costs levels for solar and wind and support schemes. Due to increasing deployment of variable renewable electricity sources (like wind and solar) in the electricity system, balancing supply and demand in the grids becomes increasingly challenging. By nature, intermittent renewable sources such as wind and solar are not always available. Therefore, fossil fuel fired power plants currently have an important function in balancing the electricity system.

However, keeping in mind the requirement for a deeply decarbonized economy in 2050, as globally decided at COP 2016 and in line with EU and Dutch energy policy, this fossil based solution will not hold anymore. Flexibility in the electricity system must be provided by CO_2 free sources and at the same time the electricity system as a whole will have to further increase flexibility and arrange for sufficient short and long term (seasonal) storage of energy. The decarbonization of industry will lead to magnification of these effects caused by an unprecedented growth in electricity consumption.

Ammonia (NH_3)
NH_3 is chosen as a potential contributing solution because it provides a pathway to fully CO_2 neutral electricity storage and generation of CO_2 neutral electricity on a scale that is not limited by scarcity of materials or storage space.

NH_3, which is currently produced, as a base chemical and feedstock for fertilizers, in very large quantities from natural gas, is a high caloric energy carrier that can be produced from renewable electricity and thus be used to store electricity. Water is electrically split into hydrogen (H_2) and oxygen, subsequently the H_2 and nitrogen from air are converted into NH_3. NH_3 has a potential to be used as a chemical storage medium due to high efficiency, energy density and low cost of nitrogen sourcing. A concern is the safe handling of NH_3, however with the large amount of experience in the chemical industry this appeared very well manageable.

Investigation
Using NH_3 as potential solution gives rise to questions like what is the attractiveness of NH_3 as a chemical storage medium? Can power-to-ammonia create enough flexibility on the one hand and avoid grid capacity increase and integration costs on the other hand?

Subject of this study is to investigate both technological and economical under what conditions NH_3

- can be produced using renewable electricity;
- can be used to store electricity;
- can be used as a fuel for an electricity production facility.

The partners in this project have studied three cases. The first case relates to electrochemical production, storage and use of NH_3 for a rural setting (Goeree-Overflakkee), avoiding grid modification costs and allowing local production of CO_2 free NH_3. The second case allows use of NH_3 as a CO_2 neutral fuel in the highly efficient Nuon Magnum gas turbine combined cycle (CCGT) power plant in the Eemshaven, thus generating flexible and CO_2 free electricity. The third case assesses the electrochemical production of NH_3 at OCI Nitrogen to replace (some of) the current, natural gas based production. Apart from assessing the economic feasibility of the above options, other relevant aspects related to power-to-ammonia including technical, operational, financial, legislative and safety issues have been evaluated as well.

Findings
We have concluded that CO_2 neutral NH_3 produced in an electrochemical way from sustainable electricity will be a feasible alternative for NH_3 produced from natural gas in the longer term.

Comparing the processes for electrochemical production of NH_3 resulted the following ranking in decreasing order of efficiency; Solid Oxide Electrolytic Cell (SOEC), Low Temperature Solid State Ammonia Synthesis (LT SSAS), Battolyser, Proton Exchange Membrane (PEM) and High Temperature SSAS (HT SSAS).

A competitive price for electrochemically produced CO_2 neutral NH_3 versus conventional natural gas based produced NH_3 (300-350 EUR/ton) can be achieved when investment costs for electrolysers drastically come down, when costs for emitting CO_2 increase significantly and when there is sufficient supply of relatively cheap CO_2 free electricity. The high investments in electrolysers require a large on-stream time to minimize costs per ton. This contradicts with the intermittency of large scale availability of renewable energy due to the production patterns of wind and solar.

Use of NH_3 as a fuel in a CCGT power station is possible by cracking the NH_3 into H_2 and nitrogen before combusting the H_2 in the gas turbine. Time to market for large scale application is estimated to be 5-10 years. As the NH_3 will be cracked into H_2 prior to combustion in the gas turbine, application of NH_3 as a fuel in the power sector enables a seamless integration with a H_2 economy. Use of NH_3 as CO_2 neutral fuel in the Nuon Magnum power station has the potential to reduce CO_2-emissions by 3.5 Mton/year when operating on base load producing 10 TWh of electricity. This reduction is 7% of the power related carbon emissions in The Netherlands in 2015.

Locally produced CO_2 neutral NH_3, as investigated in the Stedin case on Goeree-Overflakkee, will be sold on the market. The distribution of the NH_3 can be done via the NH_3 terminal in the harbour of Rotterdam.

Conclusions
Production of NH_3 using (excess) renewable energy cannot compete with existing fossil based NH_3 production. Drastic changes in production cost of electrolysers to less than 70% of the reference price of 1000 EUR/kW, supply of renewable energy and a global increase in CO_2 price are needed to make this a competing production route.

Reduction of the CO_2 footprint of NH_3 by producing it via electrochemistry rather by the conventional process from natural gas is only possible if the electricity used is renewable. In that case the CO2 footprint is zero. If electricity produced from fossil fuel is used for the electrochemical production of NH_3, the CO_2 footprint will increase by approximately a factor 3.

For grid owners, an advantage of producing NH_3 with wind and solar power will be that investments in the grid can be reduced. If the share of wind and solar power increases without demand side management and without energy storage the investment requirements in increasing grid capacity will be substantial. The combination of demand side management and local energy storage can contribute to the reduction of the necessary investments in the grid. Power-to-ammonia enables energy to be transported and stored for periods of days, weeks or even months.

Electricity storage in the form of NH_3 will add cost to the overall electricity system. However, large scale CO_2 neutral energy storage will introduce important benefits for the system, enabling a further penetration of intermittent renewable electricity sources, enabling further electrification and providing CO_2 free NH_3 as fuel and chemical commodity.

At deep decarbonisation, flexible electricity production based on application of fossil fuels during periods when supply from intermittent renewable sources is insufficient, cannot be applied unless Carbon Capture and Storage will be deployed. In other words, the initially more costly use of NH_3 as a CO_2 neutral fuel for electricity production becomes very attractive and one of the few realistic alternatives.

Only installing additional renewable wind and solar capacity is not sufficient to meet the CO_2 reduction targets of 80-95% in 2050. Large scale storage and import of renewable electricity is required to meet these targets. Power-to-ammonia enables both storage and import and has the potential to contribute substantially to CO_2 reduction targets, offering flexibility for the electricity system and allowing for an alternative to investments in electricity grid infrastructure.

1. Project overview

Project description
The Institute for Sustainable Process Technology (ISPT) has brought together various parties from different sectors of industry to study the electro-chemical production of NH_3 and the storage of electricity in ammonia (NH_3). Objective of this Power-to-ammonia (P2A) study is to investigate under what conditions NH_3 can be produced using renewable electricity, can be used to store electricity and can be used as a CO_2 neutral fuel for a power plant.

The study has elaborated value chains and business cases for green NH_3 for three different situations:

a. The NUON Eemshaven Case – use of NH_3 to import or store CO_2 -neutral energy and use it as a CO_2 free fuel for a gas turbine combined cycle (CCGT) power plant in the Eemshaven.
b. The Stedin Goeree-Overflakkee case – use of NH_3 to store energy in order to avoid investments in the power grid on the island of Goeree-Overflakkee.
c. The OCI case – use of renewable electricity rather than natural gas as feedstock for NH_3-production.

This P2A study is funded by a Topsector Energy subsidy, supplied by the Ministry of Economic Affairs and is a partnership of ISPT, Stedin Infradiensten, Nuon, ECN, Technical University Delft, University Twente, Proton Ventures, OCI Nitrogen, CE Delft and AkzoNobel.

Background
The energy system worldwide will change radically in the coming decades. The role of coal is heavily under discussion in Northern Europe. To comply with the Paris Climate Agreement, phasing out coal won't be enough and also gas will need to be decarbonized, also known as deep decarbonisation. On the demand side energy efficiency developments will balance with an increasing demand for electricity due to growth of population and replacement of oil and gas in industry and transportation by electricity (electrification). Subsidy schemes, further tightening of CO_2-regulations by governments, demands for sustainability by financial institutions and public opinion will stimulate the development of renewable energy supply. The fast decrease of the production costs for electricity produced by wind and solar is supporting this illustrated by two recently announced projects. A Dutch offshore wind park (Borssele 3 & 4) will produce electricity for 54,5 EUR/MWh and in Abu Dhabi a solar park will produce electricity for 23 USD/MWh.

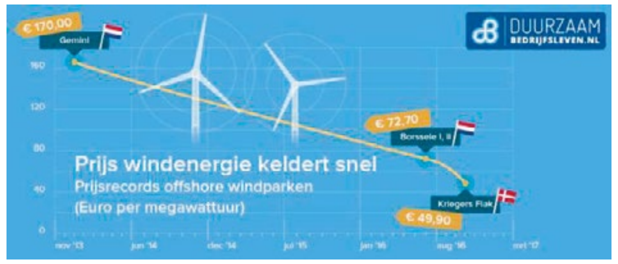

Figure 1.1: price development wind offshore

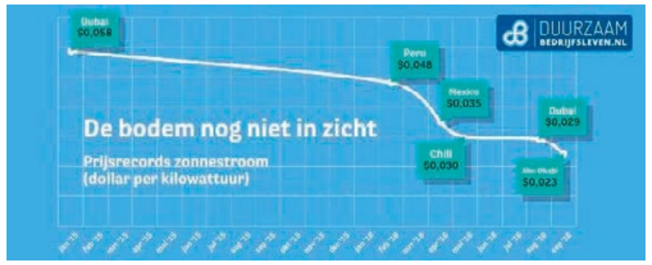

Figure 1.2: price development pv electricity

Increasing penetration of renewable electricity production makes balancing supply and demand in electricity grids necessary and challenging. Production of renewable intermittent sources such as wind and solar are depending on the weather. Currently fossil fuelled power plants are dispatched to balance the system. However, for the required deep decarbonisation, this fossil based solution will not hold anymore. However, the need to balance the electricity supply and demand remains requires demand side solutions and tends to strongly increase grid integration costs. Storing electricity as one of the solutions can be done in various ways for instance in H_2, pumped hydro power, batteries or compressed air. The preferable type of storage is depending on the amount of electricity to be stored, the required storage time and on the cost of storage. Both sufficient short and long term storage of electricity will be required as well as sufficient flexibility in the electricity system.

NH_3 if produced from renewable electricity can be used as a high caloric energy carrier to store CO_2-free electricity. NH_3 has a potential to be used as a chemical storage medium due to a relatively high round trip efficiency, energy density and low cost of nitrogen sourcing. Converting NH_3 back into electricity can be done without CO_2-emissions. The technology is scalable and not limited by scarcity of materials or storage space. It fits in the ambition of the Paris Climate Agreement to come to high CO_2 emission reductions and in the Dutch ambition to create a CO_2 neutral and fully renewable energy system 2050.

Given these developments, the use of electricity as a replacement for natural gas seems an attractive alternative to the NH_3 industry to reduce their CO_2 emissions since the production of NH_3 accounts for about 1% of the global CO_2-emissions.

NH_3 production technologies
Because of its many applications, NH_3 is in volume the second globally produced inorganic chemical. Dozens of chemical plants worldwide produce NH_3. Consuming more than 1% of all man-made energy, NH_3 production is a significant component of the world energy budget. Modern NH_3-producing plants depend on hydrogen (H_2) using steam methane reforming (SMR) to react with atmospheric nitrogen (N_2) using a catalyst under high pressure and temperature (200 bar and 450 °C) to produce anhydrous liquid NH_3. This step is known as the Haber-Bosch synthesis ($3 H_2 + N_2 \rightarrow 2 NH_3$).

An NH_3 production benchmark has been carried out to compare state of the art NH_3 production from SMR combined with Haber Bosch NH_3 synthesis on the one hand with electrochemical production technologies using electrochemical H_2 production with Haber Bosch synthesis or direct electrochemical NH_3 synthesis on the other hand. Key performance indicators of like efficiency, CO_2 avoidance and cost (EUR/ton NH_3) have been compared. The following results have been found:

- The systems in decreasing order of efficiency are SOEC, LT SSAS, battolyser, PEM and HT SSAS. Details on the technologies are provided in chapter 2.
- Per ton NH_3 produced by renewable electricity 1.8 ton CO_2 is avoided compared to natural gas based SMR. If grey electricity, based on the Dutch fuel mix[1], is used, the CO_2 emissions are three times higher compared to the one for SMR.
- The cost of NH_3 is evaluated in the year 2023 and 2030 with varying levels of fuel prices and renewable penetration. The cost of NH_3 in the year 2023 and 2030 is always higher for the electrochemical than for the SMR. However, in the year 2030 with high renewable penetration, this trend is reversing. Only SOEC and battolyser are able to achieve lower costs than the SMR in the high renewable energy scenario. These can be explained by the high efficiency of SOEC and the additional revenues generated by the battolyser by acting also as a battery.

Electricity storage technology comparison
In paragraph 2.10 a comparison has been made for different electricity storage technologies. A summary is presented in the figure below. Chemical storage has been identified as relevant for longer term to seasonal energy storage due to its high capacity, high power and relatively low cost of storage. The round-trip efficiency, defined as electricity recovered from the storage compared to the electricity input, of chemical storage options is 25% to 40%. This is lower compared to electrical options (batteries, capacitors) or mechanical options (fly wheels, Liquid Air Energy Storage (LAES) or Compressed Air Energy Storage (CAES). This is due to the multiple steps required to convert electricity into chemical energy and vice versa. It is also identified that pumped hydro features high capacity, high power, low cost and high efficiency. However, the application has geographical limitations and as such very limited potential application in The Netherlands.

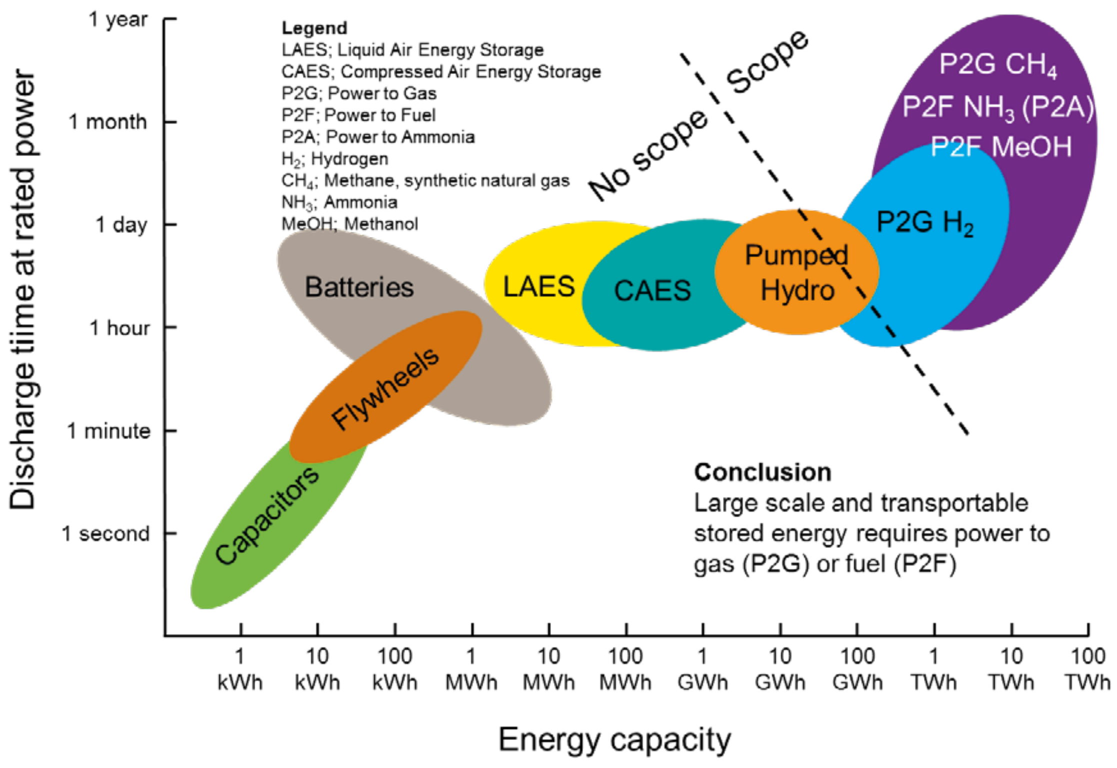

Figure 1.3: storage of electricity

Energy scenario's
CE Delft has prepared electricity scenarios up till 2030 as input for the business cases. The National Energy Outlook 2015 (NEO) fixed and intended policies was used as starting point. Based on this a low and high prices scenario was developed as well as a high renewable energy sources (RES) scenario for 2030 assuming introduction of renewables on a larger scale compared to the NEO. The main conclusions are:

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[1] Appendix B: CE Delft report

- Over time, the volatility of the electricity price is expected to increase significantly. This is most extreme in the high renewable energy sources (high-RES) scenario for 2030.
- The high-RES scenario for 2030 shows that in this scenario, featuring 28 GW_e wind and 20 GW_e solar-PV in The Netherlands, around 65% (80 TWh) of the total electricity use in The Netherlands (120 TWh) will be produced by wind and solar-PV. There is a clear need for demand response and/or energy storage that can absorb oversupply of wind and solar electricity.
- Increases in renewable electricity production lowers prices during the 900-1800 hours that the price is already relatively low (the tail of the price duration curve, see the graph below).
- The high share of renewable supply makes balancing the system more expensive during the hours with lower renewable supply, leading to higher prices. This will require flexible power production, preferably from renewable or CO_2-neutral fuels, to accommodate the times with low wind and solar electricity production.

The figure below shows the price duration curves for the simulated years under the 'high prices' fuel price scenario. This figure show the simulated hourly prices from high to low, to allow for comparison of the extremes. For reference, the 2013 Dutch day ahead market results (APX DAM) are included in grey. Raw simulation results are shown without the post-processing of the negative hours. In the most extreme scenarios (especially 2030 high-RES) this leads to large negative prices. These negative values should in no case be used for quantifying a business case. During these hours curtailment would take place.

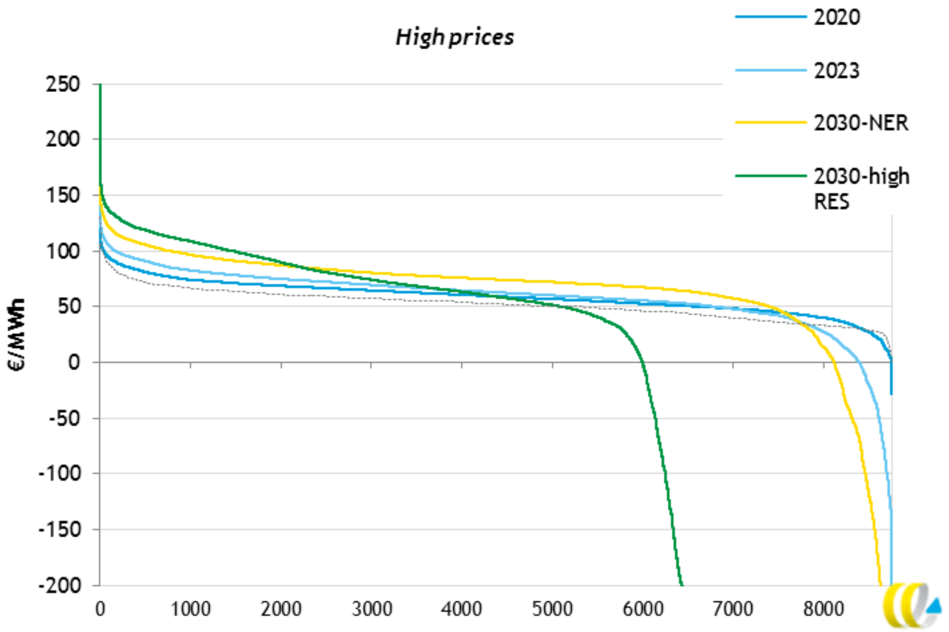

Figure 1.4: Price duration curves high RES scenario

The price information supplied by CE Delft was used by Nuon, Stedin and OCI Nitrogen in their business cases.

The Nuon Eemshaven case

The value chains has been elaborated and business cases have been investigated for the production of NH_3 from low or no CO_2 sources as a fuel for the Magnum CCGT power plant. Large scale storage (> 100 GWh_e) for a period more than weeks and also months has been elaborated.

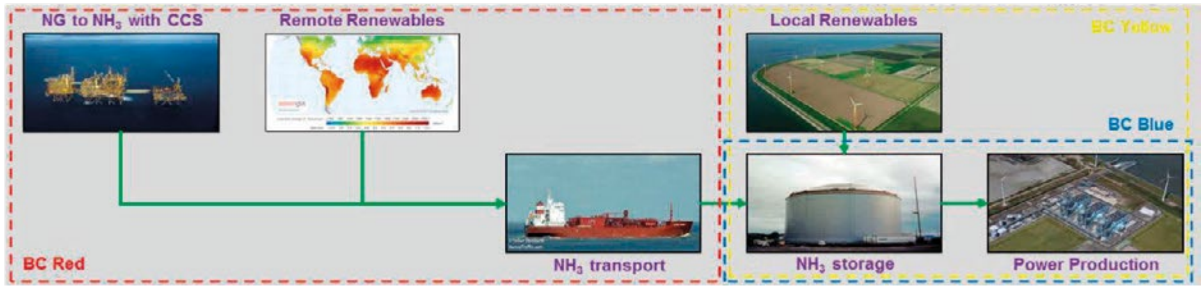

Figure 1.5: value chain Nuon Eemshaven

Options and consequences of using NH_3 as a fuel in the existing CCGT power plant were investigated.

Nuon has drawn the following conclusions:

- To accommodate volumes and duration required for longer-term storage options (weeks to months), chemical storage options are required.
- Storage by means of NH_3 compared to H_2 is much more attractive because:
  - Pressurized storage (at ambient temperatures) of limited volumes of NH_3 can be done at around 10 bar(a) while pressures required for H_2 are 350 bar(a) or higher to achieve a reasonable but still lower volumetric energy density.
  - Large scale cooled storage (at atmospheric pressure) of NH_3 can be done at -33°C while it would require a temperature of -254 °C for H_2. This very deep cryogenic conditions required expensive and energy consuming liquefaction and very special storage vessels. Due to the large temperature difference between liquid H_2 and ambient the losses over time will be substantially large compared to NH_3 storage.
- Analysis done by Nuon shows installing additional renewable wind and solar capacity in The Netherlands is not sufficient to meet the CO_2 reduction targets. Large scale storage and import is required to meet these targets. NH_3 enables both storage and import and provides a new option for achieving the CO_2 reduction targets.
- The preferred way to use NH_3 as a fuel for a CCGT is the convert it back to H_2 and N_2 by cracking. It will enable limited co-firing of cracked NH_3 with existing dry low NO_x (DLN) combustors. For 100% firing of cracked NH_3 combustion experience can be used from plants firing high H_2 content fuels. Direct firing of NH_3 would give the highest efficiency, but would require the development of a complete new combustor requiring much time, resources and investments and a probability for high NO_x-emissions. The combustor would also be bigger due to the combustion properties of NH_3.
- Using cracked NH_3 for combustion provides integration options with other H_2 consumers.
- NH_3 produced from natural gas including carbon capture and storage (CCS) or NH_3 produced from remote continuously available renewable electricity (e.g. hydro or geothermal) shows

reasonable costs. This means that the costs of electricity produced from this NH_3 are lower than 150 EUR/MWhe, making it viable for a SDE+ type subsidy regime.
- NH_3 can be used to store locally excess renewable electricity at times when prices are low. However, the economic feasibility is only positive if the investments for the electrolysers decreases drastically in combination with a high run times for the plant and a positive business model for such storage. The business model for the storage must be further elaborated.
- The main cost driver for a P2A plant are the electrolysers, being more than 60% of the total CAPEX. A target for cost reduction is 70% of the current base price of 1000 EUR/kW.

Nuon aims for co-firing cracked NH_3 as a fuel in the Eemshaven CCGT power plant in 2021 and for a full conversion in 2026.

The Stedin Goeree-Overflakkee case
On the island of Goeree-Overflakkee the local renewable electricity production from wind and solar is rapidly increasing. Moreover, a tidal facility is being investigated. This leads to a net electricity production power up to 300 MWe. The supply exceeds the electricity demand on the island, rated at maximum 30 MWe peak.

Figure 1.6: Renewable production as is and foreseen on Goeree-Overflakkee

It is foreseen that further grid investments are necessary to accommodate the increase in renewable electricity production. These investments are twofold. On the one hand investments in connecting decentralised renewable production positions to the high voltage transport network in Middelharnis are foreseen. On the other hand further increasing transportation capacity is expected e.g. investments in the substation at Middelharnis are required. A rough estimate of these investments adds up to a total of 50 MEUR. To create a more flexible electricity system, several local storage systems and conversion technologies e.g. power-to–products are being investigated.

The rationale for investigating the business case for power to NH_3 (P2A) is that locally produced electricity, could also be directly converted into valuable chemical products, not requiring any grid capacity. Therefore investing in local electricity conversion capacity adds to the grid capacity on the one hand and avoids costly investments in increasing conventional grid capacity on the other hand. This implies an important incentive for investing in conversion technology, like P2A, as part of the electricity grid originates from avoided conventional grid capacity investments. Next to this incentive, the green renewable character of the NH_3 product as well as the possibility for grid balancing services should also be valued. In this case the grid balancing services are taken into account, but not given any value.

In this study Stedin has focussed on the case where local renewable electricity is converted to NH_3 and being transported to storage at the NH_3 storage facility in the harbour of Rotterdam. The valorisation of individual streams as oxygen (O_2) and H_2 are not taken into account. For the Goeree-Overflakkee case Stedin has distinguished three different value chains cases, differing in the location as well as the connection to the electricity grid for the production of NH_3:

1. Tidal power production facility Brouwersdam. Producing NH_3 with the power that is available from the tidal power facility that is envisaged to be located in the Brouwersdam. The 25 MW_e electrolyser is connected to the tidal facility and the aim is to absorb all renewable energy directly. Connection to the grid can be avoided.
2. Directly at the grid substation Middelharnis, producing NH_3 at the distribution station near Middelharnis. At this site a number of power cables from various wind and solar production facilities are connected to the grid. Power from the grid is available at this site. A modular set-up approach of the NH_3 production units will be chosen. The maximum power that can be deployed for production is 50 MW_e. The NH_3 production facility has a capacity of 40 MW_e and is designed to add network flexibility.
3. Stand alone. Producing NH_3 at a "stand alone" wind park. In this case there will be a more fluctuating supply of power compared with the situation at Middelharnis. Moreover, there is no possibility to use power from the grid.

Stedin has come to the following conclusions:
- For all of the three cases that have been studied there is no positive business case for the production of NH_3 from electricity at this moment. This business case consists of CAPEX, including avoided investments in the grid, OPEX and a depreciation period of 10 years.
- The case where NH_3 is produced directly at the grid substation in Middelharnis has appeared most promising. The other two cases are less interesting due to the fact that the intermittent production of renewable electricity means lower utilisation of the installed assets and the need for larger and costly storage facilities for H_2 in order to operate the Haber-Bosch process section at its minimum capacity of 25%.
- Avoided grid investments are highest in the case where NH_3 is produced directly at the grid substation in Middelharnis. When taken these into account the business case still appears not attractive from a pure economic point of view. However from a societal point of view, this case is most promising because investments in the grid are being diverted to support a new sustainable initiative also offering new economic potential for Goeree-Overflakkee.
- Different scenarios for future electricity prices have shown a great variety in the outcome for the NH_3 price from business cases for the three different cases. Only for the business case directly at the grid substation in Middelharnis the scenarios are used. The other two cases have appeared to be not feasible due to other causes as mentioned
- Upside potential for the business case, apart from the expected lower cost for electrolyser technology, that will positively influence the business case can be found in;
    - Offering specific grid services of the P2A installation,

- Social award of locally produced “green” NH_3. At this moment in time, NH_3 can only be produced on Goeree-Overflakkee when the higher cost price of this NH_3 can be allocated to the zero emission “green” character of this NH_3. This means that the NH_3 can only be put in value chains that allow for a higher NH_3 price and award the “green” locally produced character. It has appeared interesting to further investigate the potential for this NH_3 as a building block for zero-emission fertilizers such as ammonium nitrate or urea.
- Accounting for a rising CO_2 penalty on competing existing technologies based on fossil resources

- An advantage of producing NH_3 with wind and solar power for the grid owners will be lower investments in the grid. If wind and solar power increases without demand side management and without electricity storage the investment in grid extensions will be substantial. A rough estimate adds up to around 50 MEUR for Goeree-Overflakkee. The combination of demand side management and local electricity storage can contribute to the reduction of the necessary investments in the grid. P2A enables electricity to be stored for periods of days, weeks or even months.

The OCI Nitrogen Geleen case

NH_3 production requires capital intensive installations and large energy flows. For electrochemical based NH_3 production the investments are even higher. In order to achieve the lowest possible cost price, energy should be cheap and the installation should run for a large number of hours, see the graph below. The availability of low cost electricity during a large percentage of the time will be a challenge.

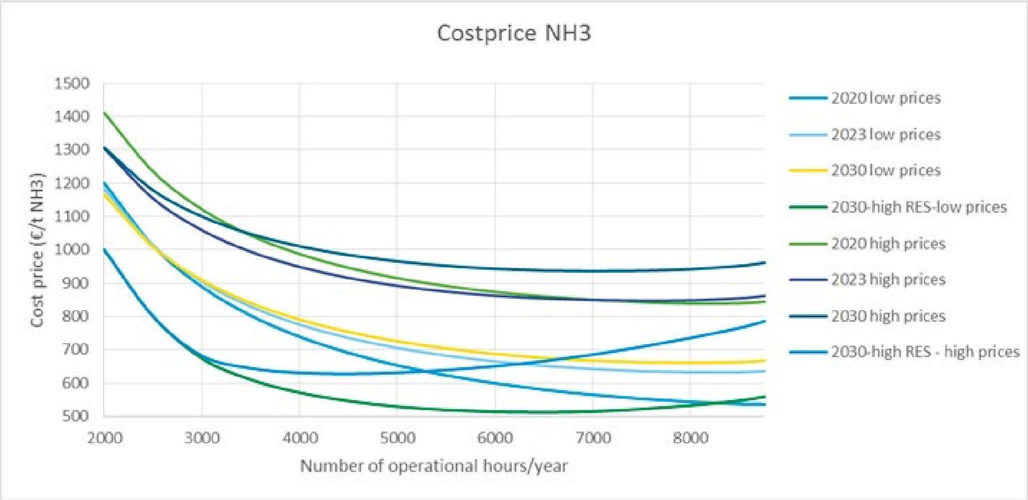

Figure 1.7: Costprice NH_3

For the short term, the costs of CO_2 free NH_3 are higher compared to the cost of NH_3 on the basis of natural gas (300-350 EUR/ton). In 2030 in high renewable energy scenario cases the price differences are smaller. With further optimisation of the operational hours the break-even point might be reached.

OCI has come to the following conclusions:

- However, if the investment, mainly in the electrolysers, could be reduced significantly and/or the pricing of renewable NH_3 is significantly higher and/or the cost for CO_2 emissions are higher, the electrification route could be profitable before the year 2030. Innovations on the electrolyser markets such as the battolyser also appeared to have a great potential. Other ways to increase profitability could be to act on both day-ahead-market and imbalance market, to include avoided investment (e.g. in power grid) and to find subsidy schemes (like SDE+/EIA) or attractive financing models.
- In order to reduce the CO_2 footprint of electrochemically produced NH_3, compared to conventional NH_3, the electricity has to come from a CO_2-free source. When using CO_2 electricity from non-renewable energy sources the CO_2 footprint is actually higher due to the efficiency loss when producing electricity.

Although the ultimate goal is to eliminate CO_2 emissions at both electricity and NH_3 production, for the traditional NH_3 suppliers it is a logical path to expect that at first the huge existing NH_3 volumes will be decarbonized before using the NH_3 for electricity production in gas fired power stations. The natural gas that is no longer used for NH_3 production can be used more efficiently to produce electricity when renewable energy is in short supply. OCI expects, usage of NH_3 on a smaller scale as a fuel for power stations, to develop sooner. This is driven by the market (consumers are willing to pay for CO_2 free electricity) and electricity suppliers looking for ways to implement this technology on a small scale.

Market applications

Based on the results of this study, the following market applications have been defined for CO_2 free NH_3:

1. It can be used as an energy carrier for power plants to produce CO_2 free electricity.
    a. The business case to produce NH_3 with renewable electricity in 2030 in North West Europe can be profitable only in a high RES scenario when the production is done at times when prices are low due to high supply and low demand in combination with reduction of the investment as illustrated in business case Red 2.
    b. This CO_2-free NH_3, used as a means of seasonal energy storage, can be used to produce electricity at times when supply of renewable electricity is low and demand is high. This option is therefore applicable for flexible back up power stations and not for base load operated power plants.
    c. The business case to produce CO_2-free NH_3 in countries where wind and/or solar power are predictable and abundant, transport large volumes to The Netherlands and use it as fuel for base load electricity production, can be profitable in combination with an SDE+ type subsidy scheme.
    d. The business cases using renewable energy sources which are available continuously like hydro or geothermal, are more attractive than intermittent sources like solar or wind.
2. NH_3 as a fuel for electricity production with CCGTs requires cracking NH_3 into H_2 and N_2 prior to combustion. The cracker also allows the delivery of CO_2 free H_2 as an alternative for non sustainable H_2.
3. CO_2 free NH_3 can also be an alternative for NH_3 produced with natural gas. This type of NH_3 has various market applications such as a green building block for the chemical industry.

CO_2-reduction
The CO_2-emission of 'green' NH_3, produced electrochemically with wind, solar or other sustainable sources of electricity, is zero. Producing NH_3 on the basis of natural gas with SMR results in 1.7-2.1 ton CO_2/ton NH_3, depending on the technology. If 'grey' electricity (on average 0.54 ton CO_2/MWh in The Netherlands[2]) is used to produce NH_3 electrochemically the emissions are around 5.5 ton CO_2/ton NH_3 based on energy consumption of 10,5 MWh/ton NH_3. This is far higher compared to the specific CO_2-emission for the SMR process. The conclusion is that using renewable electricity for P2A is a key requirement.

The current ETS system does not provide an incentive for the production of low or no carbon free NH_3. CO_2 prices should be far higher than they are today in order to make NH_3 from renewable electricity competitive. In order to make CO_2-free NH_3 price competitive, the cost per avoided ton of CO_2 producing NH_3 from renewable electricity should be in the range of 75-300 EUR per ton CO_2. The price range mainly depends on two factors: the capital expenditure (CAPEX) in relation to the operational hours and the operational expenditure (OPEX) which will be determined by the price difference between CO_2 free electricity and natural gas including CO_2 emissions costs.

However, due to the global market for NH_3 and the lack of import duties on NH_3 (based) products, such a high price would lead to carbon leakage. Carbon leakage will lead to production outside the EU often using processes with a higher CO_2 footprint.

Main Conclusion
The partners in this project have concluded that P2A has in the long term the potential to contribute substantially to CO_2 reduction targets. It offers flexibility for the energy system, can play an important role in substituting fossil based NH_3 and allows for smart choices with regard to avoiding high capacity investments in the electricity grid.

However, the production of green NH_3 from renewable electricity in The Netherlands is economically not attractive at this moment and on the short term. The main reasons are a limited availability of cheap renewable electricity resulting in a limited number of operating hours in combination with high investment costs, mainly determined by the electrolysers for the production of H_2. Attractiveness might be achieved in case the specific investment costs for electrolysers will be reduced by about 70% compared to the current level of 1000 EUR/kW or if more flexible high efficient P2A process become available like LT SSAS.

Importing NH_3 with a low or no CO_2 footprint as a fuel for carbon neutral electricity production is feasible with an SDE+ type subsidy and has the potential to contribute significantly to the required CO_2-reductions (maximum 3.5 Mton/year in case of base load operation productng 10 TWhe).

Next Steps
Flexible H_2 production in an electro-chemical way, is proven technology. But not yet on a scale necessary for the value chains subject of this report. A necessary next step is to develop this technology and make it suitable for large scale applications. Flexible NH_3 production from H_2 will also provide new challenges. Prior for companies to start employing these technologies, pilots are needed. A follow-up step would be to investigate the way in which these pilots could be eligible for subsidies.

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[2] Appendix B : CE Delft Energy en electricity price scenario's

Our conclusion is that energy storage is a major part of the route to realise CO_2-reduction. The consequence is that the government should find ways to subsidise the unprofitable top of energy storage as an extension to the SDE+ -subsidy.

In general, the analysis of production costs of the electrochemical production of NH_3 shows that the cost for electrolysers are dominant. The expectation is that the coming years the production costs of large electrolysers will decrease by scaling up, further optimisation of production processes and technological development like the battolyser in combination with stimulation of the market demand. Also new type of electrolysers are being developed. With electrolysis being a major part of the electrification of the process industry, additional research towards reduction of the production costs is needed.

2. Technology

2.1 Ammonia from SMR

Ammonia (NH_3) is currently produced from fossil fuels, air and water. Natural gas is typically used as the fossil fuel and accounts for approximately 77% of the world's NH_3 capacity. The remaining 23% is made up of plants consuming coal, heavy fuel oil or vacuum residue.

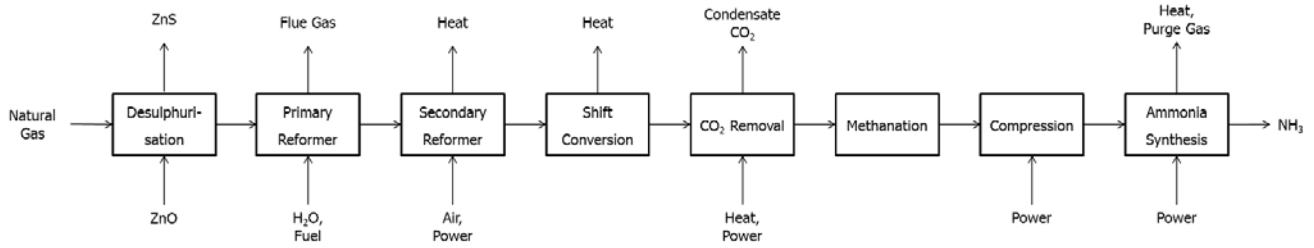

Figure 2.1: Block Diagram of Natural Gas Based Ammonia Plant (Adapted from[3])

The SMR (Steam Methane Reforming) process is shown in Figure 2.1. An important observation is that most of the process is used to produce and clean up the synthesis gas (hydrogen (H_2) and nitrogen (N_2) required to produce the NH_3. The synthesis of NH_3 only occurs in the final block.

Process Description
First, the natural gas undergoes a desulphurization process to remove any sulphur compounds. Sulphur and sulphur containing compounds are poisonous to most of the catalysts used downstream. Next, the natural gas is mixed with steam and heated (600°C) before it enters the primary reformer. Inside the primary reformer, the gas passes inside tubes that are filled with nickel containing reforming catalysts and the natural gas reacts with steam to form a mixture of carbon monoxide (CO), carbon dioxide (CO_2) and H_2. Only 30 to 40% of the natural gas present in the feed is reformed in the primary reformer, this is due to the limitation of chemical equilibria at the operating conditions. The reform reaction is highly endothermic (heat consuming). This process is supplied with additional heat provided by burning natural gas outside the tubes. The flue gas from this combustion forms one of the largest sources of emission of an NH_3 plant.

The secondary reformer is used to convert the remaining natural gas present in the primary reformer's outlet stream. The gas is mixed with process air and combusted across nickel containing secondary reformer catalysts. The air is used to supply oxygen (O_2) for combustion and the required N_2 for NH_3 synthesis. Temperatures in the secondary reformer reaches 1000°C and up to 99% of the feedstock is converted. The reforming processes produces a lot of excess heat that is used to generate steam to drive compressors and supply heat elsewhere in the process. Most of the NH_3 plants have after internal

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[3] European Fertilizer Manufacturers' Association, "Best Available Techniques for Pollution Prevention and Control in the European Fertilizer Industry," European Fertilizer Manufacturers' Association, Brussels, 2000.

use a steam surplus, which sometimes is used to generate electricity. The gas exiting the secondary reformer contains CO, CO_2, N_2, H_2, water vapour (H_2O) and other minor compounds (methanol, amines, formic acid, acetic acid etc.). The CO is converted to CO_2 and H_2 by the addition of steam and the use of the water-gas shift reaction. The minor compounds are condensed along with the water. Next, the CO_2 is removed using an amine based process to strip the CO_2 from the process gas. The NH_3 synthesis catalysts are poisoned by oxygen containing compounds, therefore, any unconverted CO and CO_2 must be removed. This is achieved using methanation, where CO and CO_2 are combined with some H_2 to form methane (CH_4) and H_2O. The water is then removed using a drying step.

The process gas now contains mainly H_2 and N_2 in the required composition for the synthesis of NH_3. The pressure of the synthesis gas is increased (to 100 – 250 bar depending on process) using centrifugal compressors and fed to the NH_3 synthesis reactor. Due to chemical equilibria limitation, only 20 to 30% of the H_2 is converted. Therefore, a recycle featuring an NH_3 condensation step is used to increase the conversion to 98%. A small purge stream is required to prevent the build-up of inerts.

2.2 Conventional power to ammonia

The power to NH_3 concept is shown in Figure 2.22. Essentially, the production and clean-up of the synthesis gas (H_2 and N_2) is simplified by using the electrolysis of H_2O to supply the H_2 and cryogenic air separation unit (ASU) to supply the N_2. In the past, NH_3 has been produced using this approach in Norway and Zimbabwe [4], however, no such plants are currently operational.

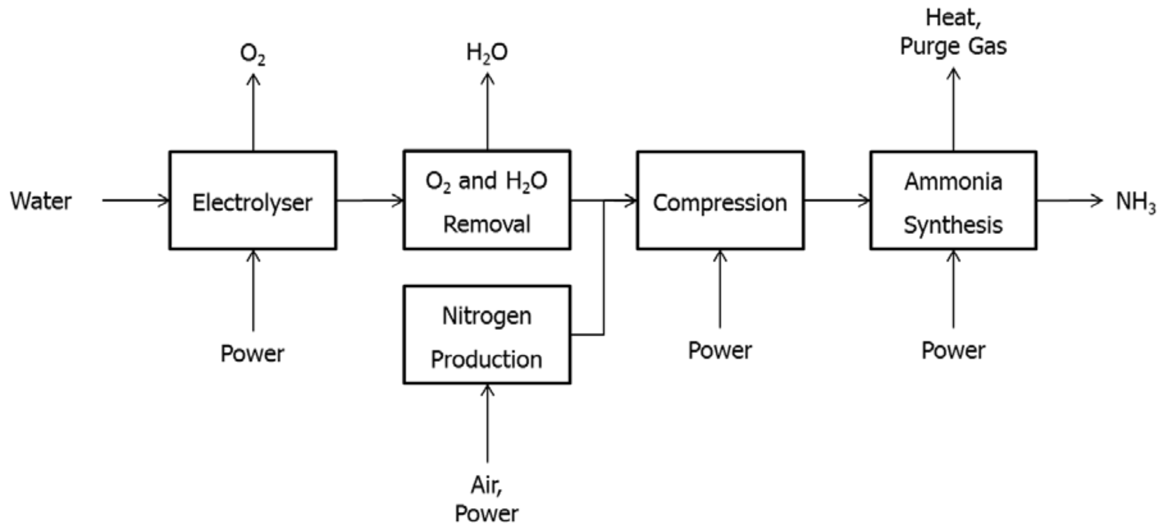

Figure 2.2: Block Diagram of Power to Ammonia

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[4] Sable Chemicals, “Technologies - Sable Chemicals,” Sable Chemicals, [Online]. Available: http://www.sablechemicals.com/technology. [Accessed 14 January 2017].

Demineralised water (H_2O) is fed to the electrolyser, where it is split into O_2 and H_2. The gas streams exit separately with limited cross-over of one component to the other side. The cross over is well below the explosive limits[5].

The exiting H_2 stream is saturated with H_2O and contains some O_2. The O_2 is removed by reacting it with the H_2 over a precious metal catalyst to form H_2O[6]. The gas mixture is passed over a zeolite bed that selectively adsorbs H_2O. The exiting gas stream is almost pure H_2.

The N_2 is produced using an ASU[7]. The N_2 and H_2 are mixed in the required composition for the synthesis of NH_3. The pressure of the synthesis gas is increased using an centrifugal compressor. Similar to the SMR process, the NH_3 synthesis is limited by chemical equilibria, therefore a recycle stream is used increase the conversion and a purge stream is used to prevent the build-up of any inerts.

2.3 Water Electrolyser Types

Water electrolysers can be divided into two types, Low Temperature (LT) and High Temperature (HT) electrolysers. As the name suggests the difference is the temperature at which electrolysis is performed. The advantage of operating at a higher temperature is the lower electrical energy input required. For example, the electrical input required at 800°C is 25% lower than at 100°C. However, additional heat input is required. The overall reaction performed by LT and HT electrolysers is the same:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

The theoretically minimal required electricity input is 39.4 kWh per kg H_2 produced at 0 °C and 1 bar(a). Practical electrolysis in industry shows higher specific electricity consumption due to the inevitable losses.

2.3.1 Low Temperature Electrolysers

Low temperature electrolysers that are currently available at commercial scales are the Proton Exchange Membrane (PEM) electrolyser and Alkaline electrolyser. Another technology that falls into the category of low temperature electrolyser is the battolyser[8] [6]. This is a dual function device that can operate as a normal battery when charging and discharging. When fully charged, the device can start performing the electrolysis of water. Only the PEM electrolyser and battolyser have been explored within this project.

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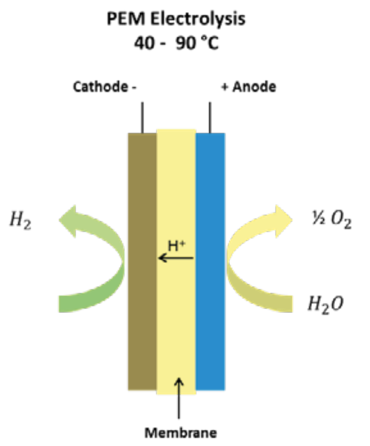
[5] V. Fateev, S. Grigoriev, P. Millet, S. Korobtsev, V. Porembskiy, M. Pepic, C. Etievant and C. Puyenchet, “Hydrogen Safety Aspects Related To High Pressure Pem Water Electrolysis,” in *Proceedings of the 2nd International Conference on Hydrogen Safety*, San Sebastian, Spain, 2007.

[6] G. Koroll, D. W. P. Lau, W. A. Dewit and W. R. C. Graham, “Catalytic Hydrogen Recombination for Nuclear Containments,” AECL Research, Manitoba, 1996.

[7] Ullmann's Encyclopedia of Industrial Chemistry, Ullmann's Encyclopedia of Industrial Chemistry - Nitrogen, Weinheim: Wiley-VCH Verlag GmbH & Co, 2005.

[8] F. M. Mulder, B. M. H. Weninger, J. Middelkoop, F. G. B. Ooms and H. Schreuders, “Efficient electricity storage with the battolyser, an integrated Ni-Fe battery and electrolyser†,” *Energy & Envioronmental Science,* 2016

A PEM electrolyser uses a solid sulfonated polystyrene as an electrolyte[9]. Commonly, Nafion® is used as the membrane. The use of a solid electrolyte allows for compact design and operation at higher pressures. The half reactions occurring in a PEM cell and the arrangement of cathode, anode and membrane are shown in Figure 2.3. The role of the membrane is to keep H_2 and O_2 separate while facilitating the transport of protons. It can be noted that H_2O is only consumed on the anode side of electrolyser, however, H_2O is actually circulated on both sides for heat management purposes. A schematic of the PEM electrolyser is shown in Figure 2.3.

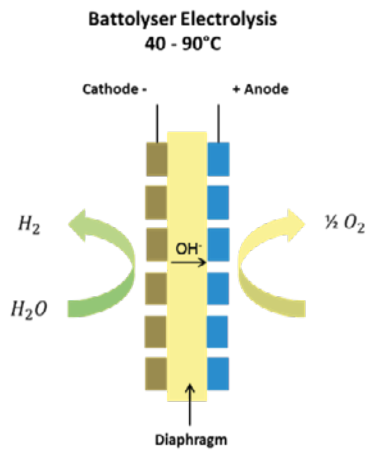


$$H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \qquad \text{Anode}$$

$$2H^+ + 2e^- \rightarrow H_2 \qquad \text{Cathode}$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad \text{Total Reaction}$$

Figure 2.3 Schematic of a PEM Electrolyser



$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \qquad \text{Anode}$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \qquad \text{Cathode}$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad \text{Total Reaction}$$

Figure 2.4. Schematic of a Battolyser

The battolyser shown in figure 2.4 uses an alkaline KOH electrolyte to conduct the OH^- ions and a polymeric diaphragm is used to separate the H_2 and O_2 while permitting the flow of OH^- ions. The electrodes are constructed from nickel and iron and when operating in battery mode, have similar characteristics to the Edison battery. The performance of electrolysis is similar to the one of an alkaline electrolyser. Once again water is circulated on both sides of the electrolyser for heat management purposes.

The Best Available Technique (BAT) specific power consumption for low temperature electrolysers is currently 53 kWh per kg H_2 produced. However, if current densities are lowered, the specific power consumption can be lowered. For the battolyser this can result in a specific power consumption of 47 kWh/kg.

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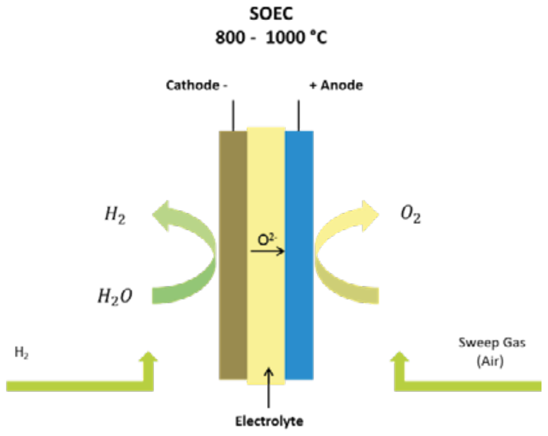
[9] M. Carmo, D. L. Fritz, J. Mergel and D. Stolten, "A comprehensive review on PEM water electrolysis," *International Journal of Hydrogen Energy,* vol. 38, pp. 4901 - 4934, 2013

2.3.2 High Temperature Electrolyser

There are currently no high temperature electrolyser commercially available, but they have been explored since the 1980s. A promising HT electrolyser is the Solid Oxide Electrolysis Cell (SOEC). This operates between 800 to 1000°C and is essentially a solid oxide fuel cell in reverse mode.



$$H_2O + 2e^- \rightarrow O^{2-} + H_2 \qquad \text{Anode}$$

$$O^{2-} \rightarrow {}^{1}/{}_{2}\,O_2 + 2e^- \qquad \text{Cathode}$$

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \qquad \text{Total Reaction}$$

Figure 2.5.Schematic of SOEC

The schematic of the SOEC is shown in Figure 2.5. The H_2 of the SOEC is 100% pure since the electrode material only allows O^{2-} ions to be conducted and therefore no cross-over of H_2 occurs. Often, a sweep gas is used on the O_2 side for temperature control purposes, however, this may not be required if operated at the thermo-neutral point. It can also be seen that some H_2 is supplied to the cathode side of the SOEC. This is to aid electrode material stability.

2.4 Solid State Ammonia Synthesis

Solid State Ammonia Synthesis (SSAS) is one of the two types of direct NH_3 synthesis that is currently being researched (the other being the use of aqueous electrolytes. There are currently no commercially available SSAS systems.

The concept is to produce NH_3 directly from a source of H_2 (from water) and N_2 (from air). The production of *gaseous* NH_3 has been achieved using SSAS at high and low temperatures with varying levels of success. The highest reported formation of NH_3 are 1.13 x 10^{-8} mol s^{-1} cm^{-2} at 80 °C and 9.5 x 10^{-9} mol s^{-1} cm^{-2} at 500 °C[10]. However, research has identified that commercially viable production rate is around 4.3 x 10^{-7} mol s^{-1} cm^{-2} or above. So the current research data are still 1 to 2 orders of maginude too low.

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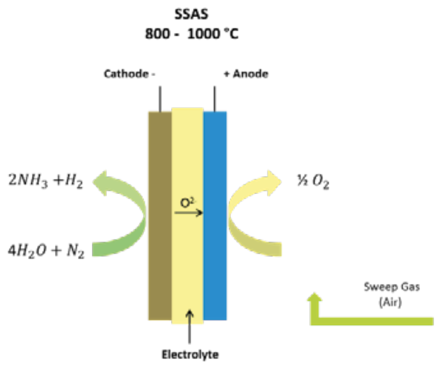
[10] I. Garagounis, V. Kyriakou, A. Skodra, E. Vasileiou and M. Stoukides, "Electrochemical synthesis of ammonia in solid elctrolyte cells," *Frontiers in Energy Research,* vol. 2, no. 1, pp. 1 - 10 , 2014.

2.4.1 High Temperature SSAS (HT SSAS)

SSAS can be divided based on the type of electrolyte cell used; either a proton (H^+) conducting or oxygen ion (O^{2-}) conducting electrolyte. The use of a high temperature (850°C) O^{2-} conducting electrolyte has been explored further within this project. A schematic of this is shown in Figure 2.6. All SSAS systems currently co-produce NH_3 and H_2, the half reactions are shown in Figure 2.6. It has been assumed that the H_2 and NH_3 are co-produced in a mole ratio of 3:1



$2O^{2-} \rightarrow \frac{3}{2}O_2 + 6e^-$	$H_2O + 2e^- \rightarrow O^{2-} + H_2$	Anode
$N_2 + 3H_2O + 6e^- \rightarrow 2NH_3 + 3O^{2-}$	$O^{2-} \rightarrow {}^1/_2\, O_2 + 2e^-$	Cathode
$N_2 + 3H_2O \rightarrow 2NH_3 + \frac{3}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	Total Reaction

Figure 2.6. Schematic of a SSAS Electrolyser[11]

2.4.2 Low Temperature SSAS (LT SSAS)

Literature shows that low temperature SSAS has achieved production of gaseous/aqueous NH_3. However, it has been theorised that the production of liquid NH_3 directly from a source of H_2 (from water) and a source of N_2 (from air) is possible. This can be achieved by operating the low temperature SSAS system at higher pressure and having an electrode arrangement such that NH_3 is produced on the opposite side to where the water is supplied. The envisaged benefits of producing anhydrous liquid NH_3 are the large reduction in system costs and improved flexibility.

2.5 P2A Flexibility

The system flexibility, quantified as response time and load range shows that PEM, battolyser and LT SSAS based power to NH_3 systems have a load range of 0 to 100% of nominal capacity and are able to ramp up from 0% to 100% in 40 minutes and turn down from 100% to 0% in 10 minutes. The total NH_3 plant, including an electrolyser section and an NH_3 synthesis section is limited in flexibility by the NH_3 synthesis section. In case of HT SSAS and SOEC as the choice of electrolysis, power to NH_3 systems have a load range of 50% to 100% and can ramp up in 25 minutes and turn down in 13 minutes. The ramp up time is limited by the NH_3 synthesis system, while the ramp down and the load range are limited by the electrolysers themselves. The main risks associated with dynamic operations are the damage of the NH_3 synthesis catalysts due to thermal cycling and the loss of containment due to H_2 embrittlement if the system is shut down and pressure is maintained. Furthermore, it can be concluded that due to the magnitude of the ramp up and turn down speeds of the full P2A system, it is not possible to operate on the smaller 15 minute or imbalance markets for the Eemshaven site nor to use an SOEC or HT SSAS at the Goeree-Overflakkee sites. However, this does not apply for the battolyser operating in the battery mode.

2.6 P2A cost drivers

Evaluation of the CAPEX has identified that the cost drivers for the year 2023 are the electrolysers and in the year 2030 all systems apart from the battolyser continue to be driven by investments in the electrolyser costs. In the year 2030 the cost driver for the battolyser system is the NH_3 synthesis. This enables the system to benefit from economies of scale, whereby the cost scales to the power of 0.6 and not linearly. The OPEX excluding feedstock are dominated by the maintenance costs. Since this is taken as 2% of the CAPEX, the trends identified in the CAPEX also holds true for the OPEX.

Additional costs are lifetime stack replacements costs. These vary between 60 and 65% of the electrolyser cost. The time to replacement is 80,000 hours of operation for low temperature units, i.e. the PEM and battolyser and 40,000 operating for the high temperature SSAS and SOEC. With the electrolyser costs being the cost drivers, the lifetime stack replacement costs can be as high as 39% of the initial CAPEX in some cases (500 MW_e PEM and SSAS). If the intermittent operation of the PEM and Battolyser are assumed to have limited or no impact on the performance, no stack replacement is required.

2.7 Ammonia storage

Up till volumes of 5.000 m^3 NH_3, the common technology to store NH_3 is as a liquid, pressurized at ambient temperature. The minimum required pressure is depending on the ambient temperature but a typical value is about 10 bar(a).

For larger volumes the common way for storing NH_3 is as a liquid at ambient pressure and at the saturation temperature of about -33 °C. To ensure containment, a double wall tank system is applied. Boil-off NH_3 is captured and returned into the tanks by a redundant system. Large storage tanks in The Netherlands are present in Geleen (2x15 kton), Rozenburg (2x15 kton) and Sluiskil (1x10 kton and 1x20 kton).

2.8 NH_3 to power

Nuon has investigated the conversion of NH_3 into power together with Twente University. The Nuon Magnum power plant in Eemshaven is considered for this analysis. This plant is commissioned in 2013 and consists of three separate natural gas (NG) fired Combined Cycle Gas Turbine (CCGT) units of 437

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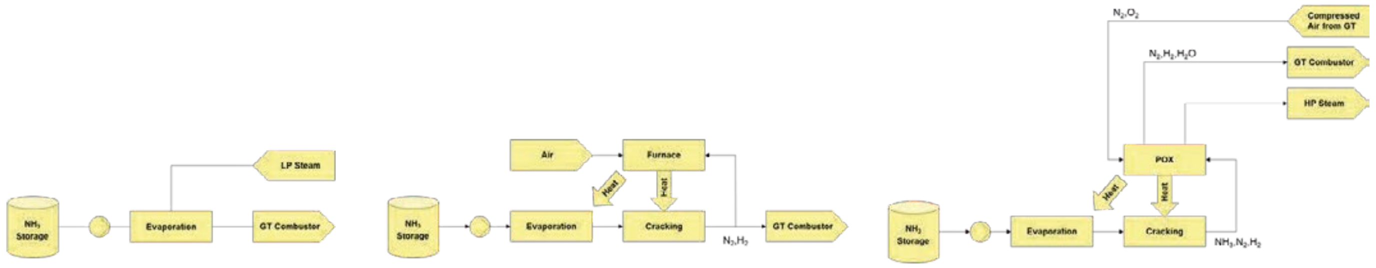
[11] I. Garagounis, V. Kyriakou, A. Skodra, E. Vasileiou and M. Stoukides, "Electrochemical synthesis of ammonia in solid elctrolyte cells," *Frontiers in Energy Research,* vol. 2, no. 1, pp. 1 - 10 , 2014.

MW_e net output each. The heart of each CCGT is a Mitsubishi Hitachi Power Systems 701F4 gas turbine (GT).
The key issue with the conversion of NH_3 to power is the combustion. Little is known about NH_3 combustion although in the past work has been performed especially on use of NH_3 for reciprocal engines. For gas turbine combustion, some research has been done on the direct combustion of NH_3, but a practical application in large scale gas turbines for power generation is remote.

Property	**Unit**	**NG**	NH_3
Lower Heating Value	MJ/kg	46.8	18.6
	MJ/Nm^3	38.9	14.1
Wobbe Index	MJ/Nm^3	48.5	18.4
Flame Speed	cm/s	40	6

Table 2.1 Comparison of typical combustion properties

In Table 2.1 an overview is given of key combustion parameters of NH_3 compared to natural gas. After consultation of gas turbine Original Equipment Manufacturers (OEMs) the conclusion is that the main issues seen with direct NH_3 combustion are the low flame speed and hence the larger flame size and the risk on high NO_x-formation due to the existence of nitrogen containing radicals during the combustion. In theory these could be mitigated by designing a new combustor in which a rich mixture is combusted resulting in low nitric oxide (NO_x) formation followed by adding secondary air to create a lean continued combustion. However such development is not part of the current research and development programs of OEMs.



Direct NH_3 combustion (NH3_DIR) NH_3 cracking (NH3_CR) NH_3 partial oxidation (NH3_POX)

Figure 2.7 NH_3 combustion options

OEMs have been developing combustors for H_2. Main driver for this development has been integrated coal gasification combined cycles (IGCCs) with Carbon Capture and Storage (CCS). This technology results in a fuel towards the gas turbine with high fractions of H_2 (>70 mol%). H_2-rich fuels can also be produced from NH_3 by cracking or partial oxidation. Cracking implies that gaseous NH_3 is heated up till 800..900 °C, resulting in a fuel consisting of 75 mol% H_2 and 25 mol% N_2. A trace of NH_3 remains, depending on the operating pressure and temperature of the cracker. In case of partial oxidation (POX) air is extracted from the compressor discharge and used to accomplish a partial combustion of NH_3, resulting in a syngas consisting of approximately 37 mol% H_2, 47 mol% N_2 and 16 mol% H_2O. The heat produced in the POX-reactor is converted into high pressure steam and converted to power in a steam turbine. In Figure 2.7 all three options are presented in a simplified way.

For all three options a performance analysis has been performed. An integrated model of the NH_3 processing from the liquid storage up to and including converting it to power in the gas turbine was made in the Enssim simulation package. The flue gas mass flow rate and temperature were put into a ThermoFlow model in order to calculate the steam turbine output. The combined results are presented in Table 2.2. The NG-DLN case represents the design of a single Magnum CCGT on NG.

Case	Unit	NG_DLN	NH3_DIR	NH3_CR	NH3_POX
Pe_GT	MWe	294,7	347,5	334,9	374,9
PR_GT	-	18,88	20,16	19,86	20,82
Pe_Nett	MWe	437,1	482,2	476,0	568,0
Y_Nett	%	>57%	56,6	53,1	49,4
m_H2C_RECOV	kWh/kg		2,93	2,75	2,56

Table 2.2 Performance evaluation for the combustion options.

Red coloured cells imply that GT limits are exceeded. Pe_GT is GT output, PR_GT is GT pressure ratio, Pe_Nett is net CCGT output and Y_Nett is the net CCGT efficiency based on LHV. M_H2C_RECOV is the electricity that can be produced per kg of NH_3, as liquid stored at ambient pressure.

The NH_3_DIR case results in the highest efficiency, but can't be pursued due to the issues with direct combustion mentioned before. The NH_3_POX case results in serious violation of mechanical limits of the gas turbine and the lowest efficiency. De-rating the gas turbine to meet the allowable mechanical limits would result in even lower efficiencies. Therefore the conclusion is that NH_3_CR is the option that should be developed.

NH_3 Crackers have been constructed in the past up till a size of 10 ton/h (NH_3). For 100% firing of a Magnum unit a capacity of about 200 ton/h is required. Currently installed Dry Low NO_x (DLN) burners for NG can handle a limited amount of H_2. If a limit of 10% H_2 input on energy basis (LHV) is assumed, a cracker with a capacity is 20 ton/h would be required.

A logical step is to demonstrate the operation of a 20 ton/h NH_3 cracker in combination with a Magnum CCGT including the existing DLN-combustors. This avoids initial investment in combustors until the cracker concept is demonstrated. Estimated timeline for the demo is 5 years (start operation in 2021). After successful closure of the demo, the cracker can be scaled up to 200 ton/h. This would take another 5 years, resulting in a COD in 2026. A condition is the this schedule also matches with expected H_2-rich combustor developments.

2.9 P2A and P2P Efficiency

The specific power consumption for the power-to-ammonia (P2A) systems, described in paragraphs 2.2, 2.3 and 2.8, are estimated as 9.5, 8.9, 7.1, 8.1 and 11 kWh per kg NH_3 for the PEM, Battolyser, SOEC, LT SSAS and HT SSAS respectively.

The power to power efficiency via NH_3 (P2P) for all of the systems have been calculated by ECN and TUDelft. A P2P efficiency of 29%, 31%, 39%, 34% and 25% are achieved for the PEM, Battolyser, SOEC, LT SSAS and HT SSAS respectively. The highest efficiency of the SOEC is attributed to its high temperature operation which enables higher electrical efficiency. The poor efficiency of HT SSAS is due to additional heat required, which must be supplied by burning some of the produced NH_3 or other alternative fuels. The impact due to the addition of heat is higher for HT SSAS then for SOEC because some of the NH_3 is produced in the electrolyser, this leads to a smaller Haber-Bosch reactor where less heat can be recovered. The P2P efficiency of the battolyser for the electricity stored for short term in the battery functionality (so without conversion to NH_3) is 82 - 90%[12] [6].

A heat integration study of the PEM, battolyser and LT SSAS systems showed that it is possible to operate without heat input. Only cooling water and small amounts of cryogenic duties are required. it is also possible to integrate the system in such a way that heat (low or intermediate pressure steam) can be generated from the NH_3 synthesis reactors. The study of the SOEC and HT SSAS shows that additional heat input is required for both systems. The SOEC requires the equivalent of 4,0% of the electrolyser power to be supplied as heat, whilst the HT SSAS requires the equivalent of 10,7% of the electrolyser power to be supplied as heat.

2.10 Comparison to other storage technologies

P2A is a way to store electrical energy in NH_3. This NH_3 can later be converted back into electrical energy by combusting it in a GTCC power plant. In this section a comparison is made with other methods for storing electrical energy on a seasonal level (TWh scale). Good seasonal storage methods should be manageable in terms of physical properties, economics and safety. A detailed study has been performed and documented in a separate report. This section shows a summary.

An extensive list of electrical storage methods has been composed by ECN, TUDelft and Nuon, containing options including batteries, flow batteries, fly wheels, compressed and liquefied air, pumped hydro and thermal and chemical storage. A first selection round was performed to create a shortlist of storage methods with high potential for seasonal storage. This selection was based on how the storage methods rank on volumetric energy density and round trip efficiency (electricity recovered from the storage versus the electricity input). The result has shown that only chemical storage methods have the desired energy density for seasonal storage applications. Another finding is that a flexible ratio between capacity and power is desired for seasonal energy storage. The ratio of power/capacity for a solar system to bridge the night is predictable. For seasonal storage this is not so much the case.

In a second selection round, a more detailed analysis has been done through a comparison of chemical storage methods with Key Performance Indicators (KPIs) from a technical, economic and health, safety & environment (HSE) point of view. All chemical storage methods convert electricity into H_2 with an electrolyser and combust the final product in a CCGT. H_2 storage in large quantities is difficult due to its very low volumetric energy density at ambient temperature and pressure. H_2 should therefore be liquefied, pressurized or reacted to another molecule to increase the energy density. In some cases this results in a synthetic fuel like NH_3, methanol (CH_3OH or MeOH) or methane (CH_4). In other cases a recyclable carrier is used like iron or Liquid Organic Hydrogen Carriers (LOHC) such as methylcyclohexane (MCH) or perhydro-dibenzyltoluene (H18-LOHC) from which the H_2 is released before combustion.

Results of the detailed analysis show that storing H_2 as a liquid is more expensive compared to NH_3, due to the liquefaction process and (the large volume) special storage tanks due to the extreme low temperature (-254 °C). Compressed H_2 storage lacks the practical ability to attain the desired scale for seasonal storage. This is due to a low energy density and availability of only small storage tanks and limited availability of caverns. The processes using LOHC show low round trip efficiencies and a low energy density. The cost of the required chemicals, the large storage required and P2P efficiency make these storage methods significantly more expensive compared to NH_3. The iron storage method has a low technology readiness level. This lack of development combined with the disadvantage of moving large amounts of solids disqualify this method as a realistic option for seasonal storage.

Technology	Physical Properties			Economics			TRL	Safety
	Pressure [bar(a)]	Temperature [°C]	Density [GJ$_e$/m3]	CAPEX (+++ = high)	Loss [%/6 months]	P2P Efficiency [%]		
Liquid H_2	ambient	-254	4.8	++	5.5	34	6-8	Explosive and cryogenic
Pressurized H_2	700	ambient	2.8	NA	-	38	6-8	Explosive, very high pressure
MCH	ambient	ambient	1.7	+++	-	24	5-7	Toxity, carcinogenous
H18-LOHC	ambient	ambient	2.0	+++	-	23	5-7	Unknown
Iron sponge	ambient	ambient	6.5	NA	-	28	3-6	Unknown
CH_4	ambient	-163	11.4	0	3.0	28	9	Explosive and cryogenic
MeOH	ambient	ambient	8.2	0	-	27	5-8	Toxity, but much industrial experience
NH_3	ambient	-33	6.8	0	0.6	30..39	4-7	Toxity, but much industrial experience

Table 2.3 Comparison of P2A as electricity storage technology with alternatives.

The options based on CH4, MeOH and NH3 show a similar order of magnitude for CAPEX. A large difference is that CH4 and MeOH require expensive and energy intense sourcing of CO2, while N2 sourcing for ammonia is relative cheap. CO2 sourcing requires a carbon capture unit at the power plant, with the additional disadvantage of decreasing round trip efficiency and not capturing all CO2 produced. Preferably the CO2 is sourced from a steel producer or from an ammonia plant, implying carbon capture and utilization (CCU), still requiring input from coal or natural gas. Storage of CH4 is preferably done in the gas grid since storage of CH4 in liquid phase as LNG is expensive due to the required liquefaction and special storage tanks. MeOH has good storage properties because it is a liquid at ambient conditions and could be stored directly with high energy density. Sustainable MeOH has a high value in transportation, since it enables oil companies to meet their sustainable obligations by admixing it to traditional fuels. Even if electric driving and H2 in trucks, busses and cars takes off, sustainable MeOH will be a very valuable fuel for shipping.

The NH_3 option has the highest potential for seasonal storage in combination with conversion back into electricity, due to high efficiency, high volumetric energy density, transportability and low cost of N_2 sourcing. Points of attention are safe handling of NH_3 and the technology readiness of NH_3 combustion. Safety is expected to be manageable with the large amount of experience outside the power industry. Combustion will be done by cracking the NH_3 into a mixture of H_2 and N_2, which is a technology being

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[12] F. M. Mulder, B. M. H. Weninger, J. Middelkoop, F. G. B. Ooms and H. Schreuders, "Efficient electricity storage with the battolyser, an integrated Ni-Fe battery and electrolyser†," *Energy & Envioronmental Science,* 2016.

developed by gas turbine OEMs. It also enables providing locally other H_2 consumers with sustainable H_2 like in transportation or in the chemical industry.

2.11 Conclusions and R&D roadmap

Conclusions & R&D roadmap

The NH_3 production benchmark compares state of the art NH_3 production from (SMR) to electrochemical production of NH_3. KPIs of power to NH_3 efficiency, CO_2 Avoided and Cost of NH_3 (EUR/ton) have been compared. The systems in decreasing order of efficiency have found to be SOEC, LT SSAS, SMR, Battolyser, PEM and HT SSAS, based on direct comparison of input of natural gas (SMR only) and electricity. CO_2 avoided is 1.8 ton per ton NH_3 if electrochemical NH_3 is produced since all of the energy demand is provided exclusively by electricity. This is only valid under the assumption of using green electricity. If grey electricity is used, the CO_2 emissions are three times higher than SMR. The production costs of NH_3 have been evaluated for the year 2023 and 2030 with varying levels of fuel prices and renewable penetration. It has been found that the production costs of NH_3 in the year 2023 and 2030 is always higher for the electrochemical than for the SMR option. However, in the year 2030 with high renewable penetration, this trend is reversed. Only the SOEC and Battolyser are able to achieve lower NH_3 production costs than the SMR. These can be attributed to the high efficiency of the SOEC and the additional revenue generated by the battolyser by acting also as a battery for short term storage.

Evaluation of the CAPEX has identified that the cost drivers for the year 2023 are the electrolysers and in the year 2030 all systems apart from the battolyser continue to be driven by investments in the electrolyser costs. The cost of the electrolysers for an electrochemical NH_3 plant is in some cases more than 60% of the total capital expenditure (CAPEX). Although electrolysis has been an industrial technology for many decades, to obtain the targeted market prices for NH_3 in 2030 performance improvement and cost reduction is needed. Back calculations show for the NUON case that the target costs for the electrolyser should be 300 EUR/kW. In all Stedin cases even without an electrolyser, the system is too expensive to operate.

Is this target feasible for the different technologies?

Projections from the European FCH-JU show a decrease in PEM electrolyser costs from 921 EUR/kW in 2023 to 600 EUR/kW in 2030[13]. For the battolyser an even lower purchased cost of 370 EUR/kW is predicted. The purchased cost of the SOEC & SSAS systems are comparable with the PEM system costs. All projections show higher prices than the target, but recent developments in PEM fuel cells show that major cost reductions (to 150 EUR/kW) are possible with mass fabrication[14].

Wat R&D is needed to reach the target costs and performance?

PEM electrolysers typically require expensive materials to achieve lifetimes and efficiencies comparable to commercial alkaline technologies. Durability has a double impact on the electrolyser economics. Reduced lifetime increases the capital cost because of depreciation is done over a shorter period of time but also because of the need to go to more expensive materials. Most R&D activities therefore focus on material and component developments. An illustration is the set of research priorities as presented by Hydrogenics[15] and shown the Table 2.4.

Technology Area	Critical Focus Areas	Importance	Understanding	Opportunity
Membrane	Reduce membrane thickness	9	High	High
	Membrane mechanical reinforcement	5	Medium	Medium
	Improve membrane dimensional stability	9	High	High
Catalyst	Catalyst loading reduction (O_2)	7	Medium	High
Protection Coating	Alternate lower cost coating materials	7	Medium	High
Accelerated Life Testing	Reduce design and material validation test time	9	Low	High
	Remove barriers for new materials market acceptance	9	Medium	High

Table 2.4 Key research priorities from the workshop “Degradation & Durability in PEM electrolysis”[16]

For the battolyser TU Delft has been calculating with limited power levels compared to the amount of electrode material (in MWh capacity) to keep the efficiency high (45 kWh/kg H_2). The penalty in efficiency when doubling the power level in the same device during electrolysis is now about 4% (so 46,8 kWh/kg H_2). A price reduction of the required electrolyser stack capabilities could therefore be obtained by choosing a 50% smaller MWh capacity and run it at a 100% higher power level. The discharge current cannot be increased by 100% for the full capacity in MWh, however, so it does lead to smaller battery capacity (although there we have a gain factor not yet accounted for of about 1.5 because we use the electrode material now ~50% more efficient than is possible in the old battery). The balance of plant will remain the same cost, however research will be performed to mitigate the efficiency loss altogether by gains on other fronts.

A second driver for cost reduction should be developing a large scale product of such battolyser and its materials inventory. Note that the raw materials cost are far below the 100 EUR/kWh in electrode materials. However further upscaling of battolyser technology will require a number of factors to be addressed. In principle we are dealing with a hybrid technology of two existing, mature, technologies: alkaline electrolysis and nickel iron batteries. To come to higher efficiencies it is advantageous to operate under pressure, as is done in alkaline electrolysis. The gas handling and electrolyte handling system, will be similar to what is available for alkaline electrolysers. The electronic system is like that of a large battery system, but simpler because there is no need for overcharge protections. The exact dimensioning of all components will be subject to further development. It is anticipated that upscaling can be performed without fundamental research needs. An scaled-up version will need testing in

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[13] L. Bertuccioli, A. Chan, D. Hart, F. Lehner, B. Madden and E. Standen, “Study on development of water electrolysis in the EU,” E4tech Sàrl with Element Energy Ltd, Cambridge, 2014.

[14] B. Biebuyck, “State of Play at the fuel cells and hydrogen joint undertaking”, Nederlands Waterstof and Brandstofcel associatie (NWBA), Arnhem, 8 December 2016.

[15] First International Workshop Durability and Degradation Issues in PEM Electrolysis Cells and its Components, March 12th-13th, 2013, Fraunhofer ISE, Freiburg, Germany.

[16] https://www.ecn.nl/nl/nieuws/item/start-van-electre-project-verlagen-van-electrolyzer-kosten-door-verlenging-levensduur/

various applications as short term battery storage operating for grid balancing purposes, operating as battery on a 15 minutes basis of charge/discharge, as H_2 source for short and long duration and integrated with subsequent processing of the produced H_2. Also operational parameters like the temperature and pressure control, safety aspects, and gas quality, need testing in a real large scale test environment. Within an STW project developments and improvements are being investigated to come to further efficiency enhancements with respect to the materials use, cost of materials, and device layout. These developments may be incorporated in later scaled-up versions.

Current Solid State Ammonia Synthesis (SSAS) operate at high temperature and co-produce NH_3 and H_2. Total energy efficiency of electricity to NH_3 and H_2 combined will be around 60-80%, with the NH_3 and H_2 being co-produced in a mole ratio of 1:3. The target for the SSAS it to move towards 65 to 70% total energy efficiency for the production of pure NH_3. Additional improvements are required in areas of material durability and conditions of operation (pressure and temperature).

For importing or storing intermitted renewable electricity such as remote solar or local wind, further technological developments are required. Next to low cost electrolysers, low temperature direct NH_3 synthesis (LT SSAS) is a promising technology. For the LT SSAS a documented proof of principle is required including a cost estimate. This to position LT SSAS compared to the other power to NH_3 technologies. Key objectives should be low CAPEX and switch on/off capabilities. The research on LT SSAS should lead to a device having a stack cost below that of a PEM electrolyser. In addition it should lead to the removal of the Haber-Bosch NH_3 synthesis unit and H_2 compressors when H_2 is absent in the product. These should lead to the main cost reduction of the unit overall. Research is needed to bring selectivity, efficiency, current rates and durability forward.

For the NUON case an extra technical challenge is the scale up of the NH_3 cracker and its flexibility. NH_3 crackers are available, for example to start-up NH_3 plants, but at a limited scale. A scale up by a factor of 10 is required. Another challenge is to optimize the flexibility of these crackers, since the CCGT should be operated in a flexible way. Flexibility shall be seen as ramping capabilities, short start-up and shut down times and/or very low turn down or hot stand by.

3. Value chains and business cases

3.1 World market of ammonia

NH_3 is one of the most commonly produced industrial chemicals. At this moment the annual production of NH_3 is approximately 180 million tons. The expected yearly growth of this production is between 1 and 1.5 %. Approximately 12% (21 million tons) is produced in Europe, of which The Netherlands produce around 2.7 million tons yearly. This is done by two multinationals: Yara in Sluiskil and OCI Nitrogen in Geleen.

Most of the produced NH_3 (approx. 90%) is used as a feedstock at production sites. The remaining 10% (around 20 million ton per year) is traded and transported often covering large distances. This is due to large regional unbalances in production and consumption over the world. Therefore, the NH_3 business is a global market. Western Europe and the US are two importers of NH_3. Prices in North West Europe are currently determined by the so-called Black Sea prices (Ukraine) plus the costs for transport and duties (in total approx. 80-90 USD/ton). The main parameter that determines the NH_3 production costs are the equivalent energy costs of the natural gas that is used as the feedstock (except for India and China). This means that production costs are heavily influenced by the gas and also oil prices. Although oil and gas prices are no longer coupled (in Western Europe), they still both affect the NH_3 price (as is the coal price). The large energy consumers (industry, transport, power) have flexibility options where they can switch fuels if prices differ too much. This will create a bandwidth for the NH_3 price. Driven by low shale gas prices, a lot of NH_3 production capacity is currently being installed in the US, however still not enough to make the US an exporting country.

The NH_3 consumer price is also determined by availability and demand. In the period 2011 - 2014 the consumer price was relatively high compared to today (2017, Q1) in a period of rather low consumer prices. The expectation is that the consumer prices will slowly increase the coming years. The total costs for the consumer also depend on the distance to a production facility, harbour, terminal or pipeline feed. This means that the total costs of NH_3 for the customer can be 100 to 200 USD per ton higher than production cost, due to transportation and storage cost.

Around 90% of the total NH_3 consumption is used as feedstock for fertilizers. In figure 3.1 you see that mainly urea (CH_4N_2O) is used as fertiliser. Urea is formed by reacting NH_3 with CO_2.

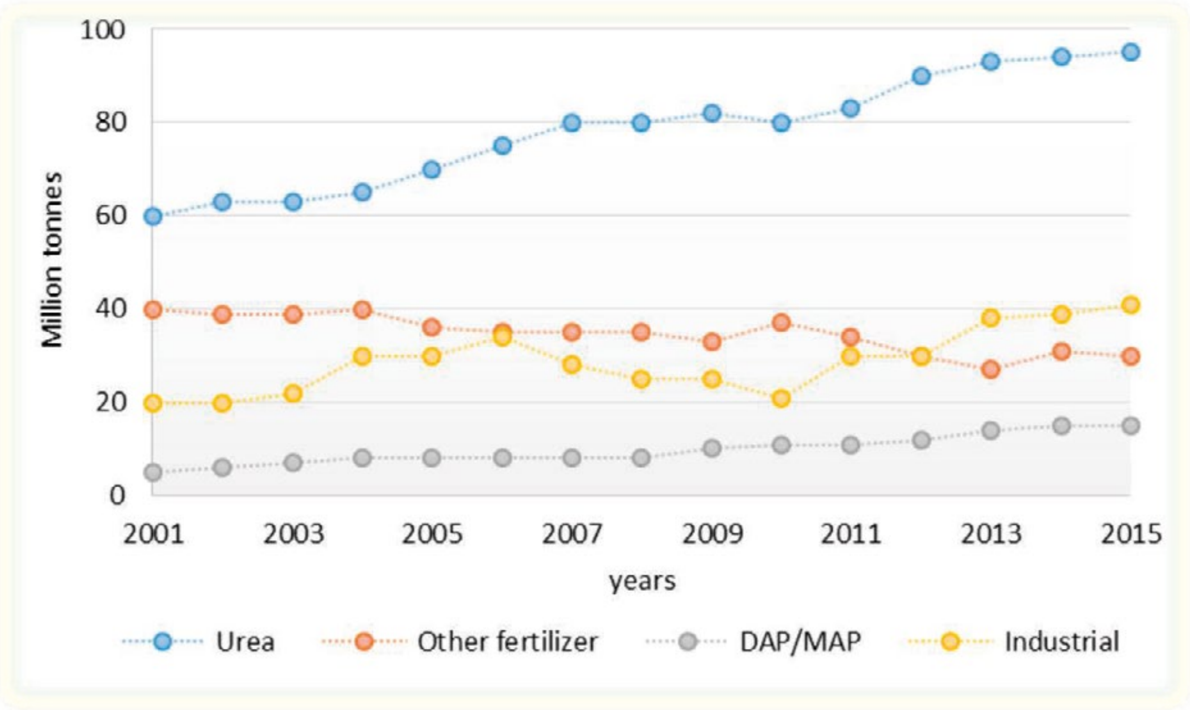

Figure 3.1 Development of NH3 consumption by application

The other fertilisers include: pure and aqueous NH_3, ammonium nitrate, ammonium sulphate add ammonium phosphate fertilizers like DAP and MAP. Pure and aqueous NH_3 are also used as fertilisers together with p.a. ammonium nitrate (also explosive), ammonium sulphate and ammonium phosphate fertilisers like DAP and MAP.

The technical applications of NH_3 are diverse. A few of them are Caprolactam, Acrylonitrile and Methyl Methacrylate. The latter two being the most important applications of technical NH_3. NH_3 is also used to prevent the emission of NO_x in power plants ($DeNO_x$-application). As an alternative, urea can be used for this purpose. Diluted urea is also used in trucks, cars and vessels to prevent emissions of NO_x. The commercial name is AdBlue. In the US it is called DEF.

With urea as feedstock a lot of products can be produced like melamine, resins, medicines and cosmetics.

Another important use of NH_3 is the production of nitric acid and all the products that need nitric acid as a feedstock. A large application for technical nitric acid is the production of ammonium nitrate in the application as an explosive agent. Finally, the use of NH_3 as a coolant in refrigeration installations and the use of nitric acid for industrial cleaning are mentioned here.

3.2 Eemshaven case

3.2.1 Rationale

Although the power plants in The Netherlands combusting natural gas are highly efficient, they still produce about 380 kg of CO_2 per MWh of electrical output. Reducing CO_2-emissions is the main driver for introducing renewable generating capacity. For the analysis, the assumed development of CO_2 emissions in The Netherlands is presented in Figure 3.3. Starting point is the national CO_2-emission in 1990, being 222 Mton. A subdivision is made across different sectors. In 1990 the CO_2-emission from power generation in The Netherlands was about 44 Mton. This figure includes all power plants, so not only the power stations operated by Nuon.

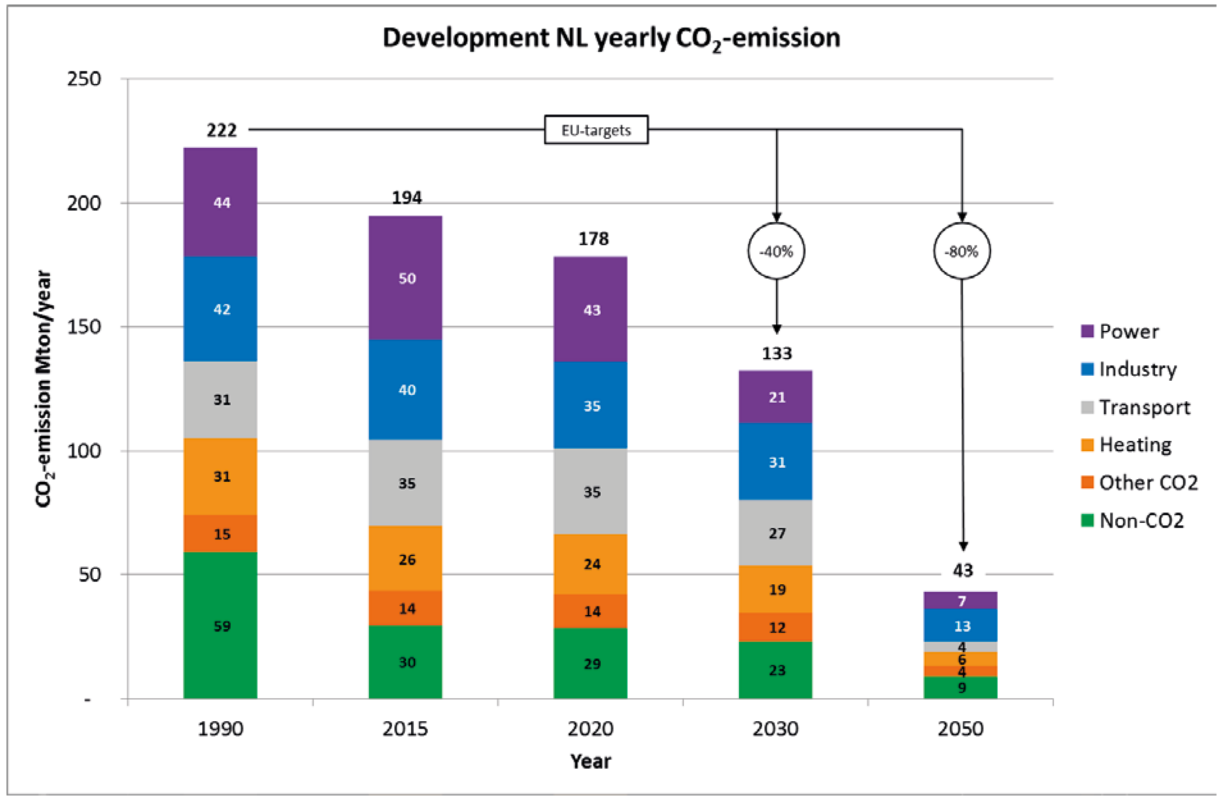

Figure 3.2 CO2 emission reduction targets

The Urgenda verdict[17] requires a reduction of 25% in 2020 with 1990 as reference, hence a maximum emission of 167 Mton on an annual basis. In the National Energy Outlook[18] it is expected that the overall emission will be between 165 and 178 Mton/year, 171 Mton/year on average.

The target set by the EU for 2030 is 40% reduction compared to 1990 levels, resulting in 133 Mton on an annual basis for The Netherlands. In this analysis it is assumed that this results in a sub target setting of 21 Mton/year for the power generation sector. The National Energy Outlook mentions expected CO_2-emissions for 2030 to be between 150 and 186 Mton/year, which is 168 Mton/year on

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[17] Rechtbank Den Haag 24 juni 2015 http://deeplink.rechtspraak.nl/uitspraak?id=ECLI:NL:RBDHA:2015:7145

[18] ECN a.o. The National Energy Outlook (Nationale Energieverkenning) 2016

average and resulting in 37 Mton/year for the power generation sector. This means that without additional measures the 2030 target of 21 Mton/year for the power generation sector will not be met. The EU target for 2050 is 80% to 95% reduction compared to 1990 levels, resulting in an overall allowed CO_2-emission of 43 Mton/year. In this analysis it is assumed that this results in a sub target setting of 7 Mton/year for power generation.

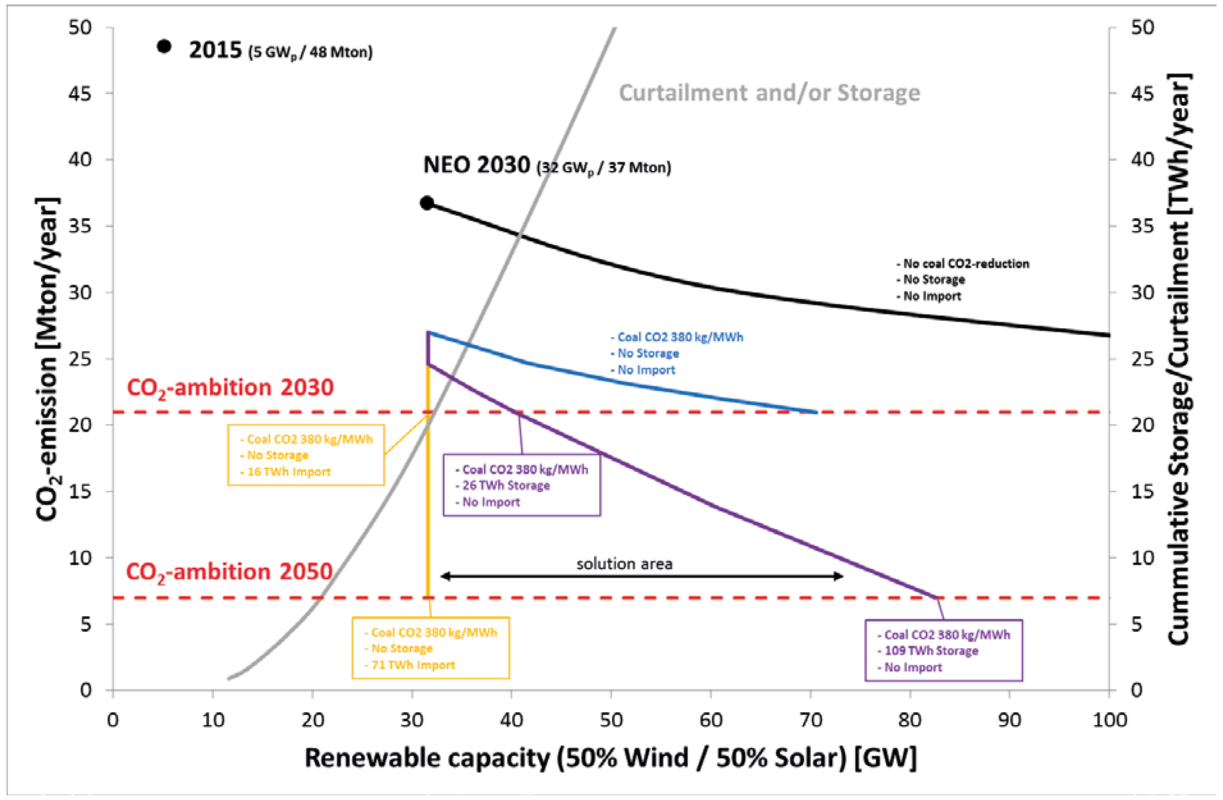

Figure 3.3 The need for renewable energy storage and/or import within the power sector

In figure 3.3 the relation between installed variable renewable capacity (horizontal) and CO_2-emission (vertical left) for the power generation sector is given. It considers The Netherlands as an island, without interconnectors. The 2030 and 2050 CO_2 emission targets for the power generation sector are plotted as red dashed lines. The 2015 situation is plotted in the left top corner as 5 GWep renewable capacity (1 GWep of solar and 4 GWep of wind), about 100 TWh/year annual electricity demand and an annual CO_2-emission of 48 Mton/year.

According to NEO[19] the total renewable capacity is expected to be 32 GWep by 2030, being 15 GWep solar and 17 GWep wind. The yearly total electricity demand is expected to be 120 TWh/year. If coal fired generation emits 750 kg/MWh, the CO_2-emission due to power generation including the 4.7 GWe coal will be about 37 Mton/year. By just installing additional renewable capacity the 2030 target cannot be met (black line). If it is assumed that coal fired generation will have a mandatory upper CO_2 emission limit of 380 kg/MWh(e) by biomass co-firing, CCS or replacement by natural gas via CCGT, the 2030 target can be met by installing about 40 GWep additional wind and solar. However, this will

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[19] ECN a.o. The National Energy Outlook (Nationale Energieverkenning) 2016

result in a considerable amount of curtailment (grey line, to be read on right axis). This is caused by the fact that an increasing renewable capacity will increase the periods of time where the electricity production is larger than the demand. By storing this excess renewable electricity in synthetic fuel and feed it back into the grid when there is a shortage, the 2030 target can be met by only installing another 10 GWep of wind and solar (purple line) and 50 GWep to meet the 2050 target.

An alternative solution is to install no additional wind and solar and import renewable electricity by interconnectors and/or synthetic fuels. To meet the 2030 target for the power generation sector an amount of 16 TWhe import would be required (yellow line). For 2050 this would be 71 TWhe.

An optimisation can be achieved within the limits of the import and storage scenario's. In the above figure 3.3 the electricity sector is considered. As can be seen in figure 3.3 also the other sectors industry, transport, heating, and other need to be decarbonised. Heating with electric heat pumps and electrical transport may be dominant options for decarbonisation of these sectors. This may require additional electricity and therefore also a different amount of installed renewables.

3.2.2 Value chain and business case structure

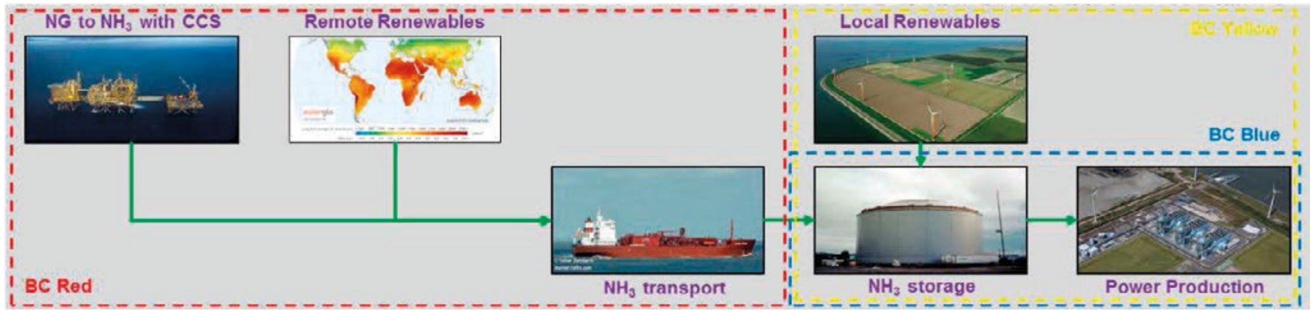

Figure 3.4: NH_3 value chains for Nuon Eemshaven.

In Figure 3.4 the high-level setup of the value chain is given. In the analysis performed, three separate business cases have been assessed:

- **Storing excess power as NH_3 (business case Yellow)**
  During times of low demand and high electricity production from variable renewable electricity sources (VRES), electricity is converted into H_2 using electrolysers and subsequently converted to NH_3. At the Nuon Magnum site the NH_3 is stored and converted back into power during periods of high demand and low production from VRES. In this way, Magnum operates as a "super battery".

- **NH_3 production and transportation (business case Red)**
  CO_2-free ammonia (NH_3) is produced from renewable sources (wind, solar, geothermal) or CO_2 free sources (e.g. natural gas with Carbon Capture and Storage (CCS)) from remote sources (i.e. outside The Netherlands). NH_3 is produced at the remote location and transported to the site of the Nuon Magnum plant. There are several technical options to produce NH_3.

- **NH_3 storage and combustion (business case Blue)**
  At the Nuon Magnum site NH_3 is stored, as production and consumption will not happen simultaneously. As the final step, the NH_3 will be converted (back) into power using the Nuon Magnum CCGT.

3.2.3 Remote NH_3 production (BC Red)

In this business case, the costs to produce NH_3 and transport it to the Nuon Magnum site have been assessed. The following main options for the business case Red have been considered:

Red 1	Reforming of natural gas (mainly CH_4) into H_2 and subsequent shifting of H_2 into NH_3. CO_2 is captured and stored. Transportation of NH_3 by means of seagoing vessel.
Red 2	Remote production of NH_3 by converting PV-generated electricity into H2 and subsequent conversion of H_2 into NH_3. Transportation of NH_3 by means of seagoing vessel.
Red 3	Remote production of NH_3 by converting electricity generated from a baseload renewable source (e.g. geothermal, hydro) into H_2 and subsequent conversion of H_2 into NH_3. Transportation of NH_3 by means of seagoing vessel.

Table 3.1 options business case Red

For the cost calculations of the Red business cases it is assumed that supply of NH_3 will start per 1-1-2026.

3.2.3.1. Business case Red 1 (CH_4 with CCS to NH_3)

In this option, NH_3 is produced from CH_4 based on the steam reforming (SMR) process. Subsequently CO_2 is captured and stored in a (offshore) depleted natural gas field. NH_3 production is assumed to take place at the remote location and NH_3 is transported to the Magnum site by means of vessels.

For the NH_3 cost it is assumed that the CH_4 feedstock can be sourced at a price of 17 EUR/MWhth,HHV under a long-term contract including CO_2 storage. This is in line with current (end 2016) TTF gas prices and constitutes a premium of 3.60 EUR/MWhth,HHV on top of the 2020 CH_4 price in the "low prices" scenario.

Using a correlation formula between CH_4 price based on historic data, this results in a NH_3 cost of approximately 300-350 EUR/ton CFR Eemshaven. Based on consultation with market parties, this appears to be a feasible and realistic price level.

3.2.3.2. Business case Red 2 (Remote NH_3 production from PV-generated electricity)

In this option, electricity produced by means of a PV-installation at a sunny location (e.g. Middle East or southern Europe) is converted into H_2 by means of electrolysis and subsequently converted into NH_3. Then the NH_3 is transported to Eemshaven by means of seagoing vessels.

As prices of electricity generated from solar energy are dropping very rapidly, PV generated electricity has become a potentially interesting source for NH_3 production based on renewable sources. In 2016 alone, prices have dropped by approximately 50% (from 48 USD/MWhe according to the recent record bid by Jinkosolar/ Marubeni of 24 USD/MWhe for a large scale Abu Dhabi project)[20].

A key issue in this business case is how the (daily) fluctuations of the electricity supply should be accommodated. Several options have been assessed. It was concluded that a configuration in which the NH_3 plant (including Air Separation Unit) is operated in a base load pattern, while running the electrolysers in a flexible pattern in line with the profile of the generated solar electricity is the most economical option. Excess H_2 produced during the day is stored in a pressurized tank and converted to NH_3 during periods of low electricity supply/ H_2 -production (see Figure 3.5).

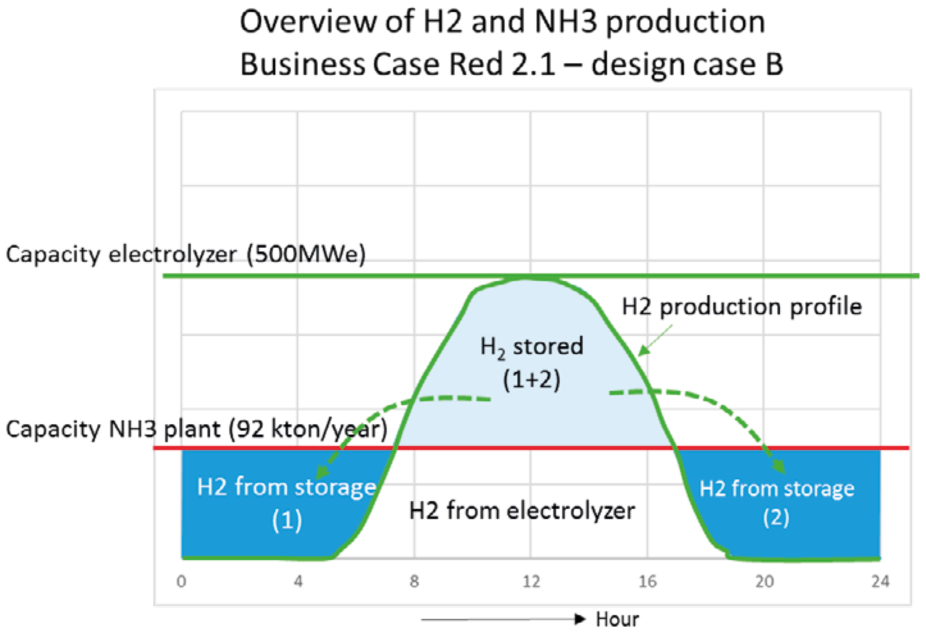

Figure 3.5: Production profile of H_2 and NH_3 for business case Red 2
Baseload operation of NH_3 plant, flexible operation of electrolysers, with H_2 stored to cover daily volatility of electricity supply

For the calculations, cost estimate data based on the 500 MWe (input) electrolyser case has been used. As the technology option the battolyser has been assumed, in combination with the Haber-Bosch NH_3 synthesis process. Prices of PV-generated electricity are expected to drop even further compared to current levels. Therefore, an electricity price of 15 EUR/MWhe has been assumed. This is a 35% reduction compared to Abu Dhabi project mentioned above. Furthermore, a load factor of the electrolysers of 0.19 has been used, in line with the electricity supplied by means of the PV-installation. A complete overview the key assumptions is provided in Appendix D.

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[20] https://www.bloomberg.com/news/articles/2016-09-19/cheapest-solar-on-record-said-to-be-offered-for-abu-dhabi

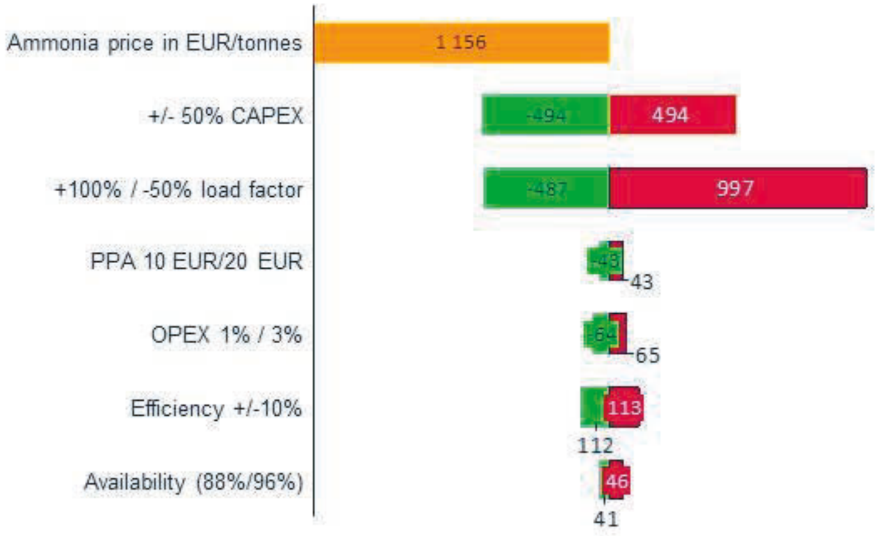

Figure 3.6 Sensitivity analysis business case Red 2

Figure 3.6 shows the valuation results for business case Red 2. It can be concluded that based on the current assumptions, the resulting costs for NH_3 are very high (up to >1000 EUR/ton NH_3 in the base case).

Specifically, this means that the price for NH_3 produced in business case Red 2 is considerably higher than market prices of NH_3 and considerably higher than the cost for the Red 1 and Red 3 business cases.

The high costs are primarily caused by the combination of the low load factor of the electrolysers (19% of maximum output) due to the delivery profile of the PV-generated electricity in combination with the high specific investments.

A combination of renewable electricity sources and/or a cheap solution to store excess electricity (e.g. an existing pumped hydro installation) is required to achieve NH_3 price levels which are comparable to alternative options. Also, a technological breakthrough (e.g. significantly cheaper electrolysers/SSAS) can contribute to required reductions in production costs.

3.2.3.3. Business Case Red 3 (Remote NH_3 production from a baseload/ controllable electricity source)

In this option, electricity produced by means of a base load source of CO_2-free electricity (e.g. geothermal or hydro) is converted into H_2 by means of electrolysis and subsequently converted into NH_3. Then the NH_3 is transported to Eemshaven by means of seagoing vessels. In the base case an electricity price of 25 EUR/MWh(e) is taken.

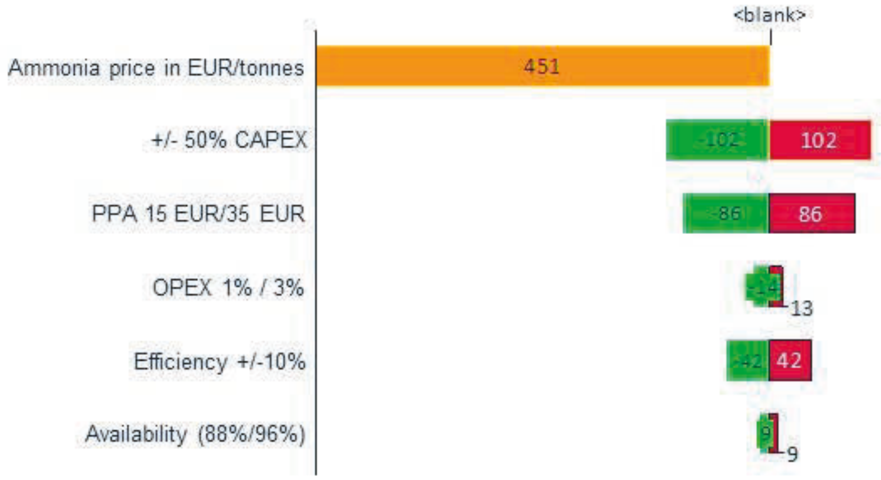

Figure 3.7 Sensitivity analysis business case Red 3

Unlike the Red 2 business case, the electricity supply has a base load character (an availability of 100% is assumed), resulting in a very high load factor of the electrolyser and no need for intermediate storage or buffering of H_2 to enable a constant production of NH_3.

Similar to the Red 2 business case, cost estimate data based on the 500 MW_e (input) electrolyser case has been used. As the technology option the battolysers has been assumed, in combination with the Haber-Bosch NH_3 synthesis process. A complete overview the key assumptions is provided in Appendix D.

Figure 3.7 shows the valuation results for business case Red 3. It can be concluded that costs of the NH_3 are significantly lower than for the Red 2 business case. The main drivers for the NH_3 cost are the electricity price and CAPEX. NH_3 costs are between 365 and 500 EUR/ton, and with a combination of optimistic assumptions on CAPEX and power price, a NH_3 cost of 260-370 EUR/ton can be achieved. Depending on developments regarding in particular CAPEX of the electrolysers and the ability to source sufficient amounts of electricity cheaply, this has the potential of becoming the cheapest source of NH_3 for Nuon Magnum.

It can be concluded that the Red 3 business case results in significantly lower costs to produce NH_3 from renewable electricity sources than the Red 2 business case.

3.2.4 NH_3 to power (BC Blue)

In this business case, the economics to store NH_3 on-site and combust the NH_3 in the Magnum power plant are assessed. The following main options for the business case Blue have been considered:

Blue 1	Co-firing of 10% NH_3 (LHV) by means of cracking into H_2. To be financed as an SDE+ (or alternative)- type project.
Blue 2	100% firing of NH_3 in one Magnum CCGT unit by means of cracking into H_2. To be financed as an SDE+ (or alternative)- type project.

Table 3.2 options business case Blue

Start of operations for the business case Blue 1 is assumed to be on 1-1-2021 and for the Blue 2 business case this is 1-1-2026.

Objective of the analysis is to verify if the costs of NH_3-combustion in Nuon Magnum are at a level that is competitive with other technologies that have the potential to produce CO_2-free electricity (such as biomass combustion, coal, or natural gas with CCS). This implies that costs should not exceed the range of 100-150 EUR/MWhe, which is considered to be the upper cost limit range for flexible CO_2 -free electricity production.

To calculate the costs of NH_3 combustion in the Blue business cases, the Blue business cases are benchmarked against a case in which Nuon Magnum will continue to be operated on natural gas.

As in the assessed scenarios NH_3 combustion is more expensive than continued operations on natural gas, mainly because of the higher fuel costs and the required investments, subsidy is required to compensate for the additional costs of generating flexible CO_2-free electricity. An SDE+ -type of subsidy is assumed for the Blue business case, meaning that subsidy per produced MWhe is provided.

The amount of subsidy needed is depending on costs of NH_3 combustion in Magnum (mainly driven by investments requirements, operating hours and the price of NH_3), the costs of operations on natural gas and the development of market prices (electricity, CO_2 and fuel). The costs of operations on natural gas is important for the amount of subsidy since this is the so-called reference case the business case is compared to. This means that when this reference case is one calculated with price scenarios containing of positive developments of spark spreads, it will be harder for NH_3 combustion to beat the operations on natural gas case, resulting in a higher required subsidy. On the other hand, a reference case calculated with a negative outlook in terms of spark spreads will be a lot easier to beat for NH_3 combustion, resulting in a lower required subsidy.

3.2.4.1. Business case Blue 1 (10% co-firing)

As outlined in paragraph 2.8 the preferred way of co-firing NH_3 is by means of cracking the NH_3 into H_2 and N_2 prior to combustion. A co-firing of approximately 10% H_2 on energy (LHV) input is assumed technically feasible and used here.

To combust this volume of NH_3, a cracker with a capacity of 20 ton/h NH_3 is needed. Additionally, some relatively minor investments in the GT are required. Also investments in unloading and storage infrastructure are needed to accommodate receipt of seagoing NH_3 loaded vessels. A total CAPEX of

50 MEUR is assumed for this business case, however this CAPEX estimate needs to be further validated.

An SDE+ -type of subsidy is assumed to be available for business case Blue 1, meaning that subsidy per produced MWhe is provided. For Blue 1 it is assumed that subsidy will be granted for a duration of 15 years, and subsidy is only granted over the 10% of electricity that is produced with NH_3.

Due to the relatively low co-firing fraction of NH_3, the operating hours of the power plant are determined by the number of hours the power plant can make money when fired on natural gas. The number of operating hours is primarily determined by the electricity price, the natural gas price and the CO_2 price. A dispatch model has been used to calculate the number of operating hours of the power plant, taking also the power plant characteristics such as efficiency and costs to start-up and shut-down the plant into account.

Based on the CE Delft price curves, the Magnum power plant will operate between 1800-2000 hours per year on average using natural gas as the primary fuel during the 15-year period in which SDE+ -subsidy is provided for the co-firing of the NH_3.

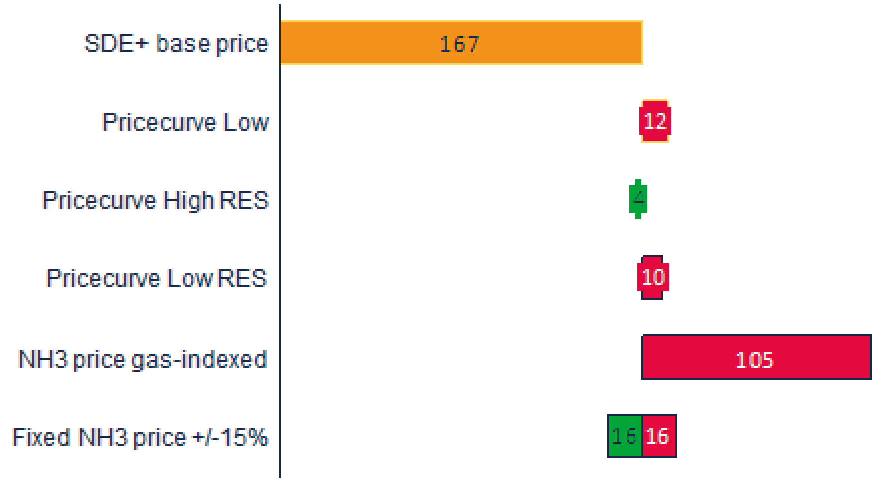

Figure 3.8 Sensitivity analysis business case Blue 1

For the NH_3 price, two scenarios have been analysed. In the first scenario a fixed target price of 300 EUR/ton is taken for the entire co-firing period of 15 years. This target price of 300 EUR/ton (or approx. 58 EUR/$MWh_{th,LHV}$) is considered to be the approx. upper allowed marginal cost limit required to achieve an electricity cost in the range of 100-150 EUR/MWh_e. In the second scenario a CH_4 -indexed NH_3 -price is taken. An overview of the main valuation assumptions for the Blue business cases is given in Appendix C.

Based on the analysis that have been performed, it can be concluded that the upper limit of the target cost (150 EUR/MWh_e) cannot be achieved in the co-firing case. Depending on the market price scenario, the costs to produce electricity from NH_3 in the co-firing case are approximately 165-180 EUR/MWh_e. When the NH_3 price is indexed to the CH_4 -price, costs increase to cost levels above 200 EUR/MWh_e, depending in the price scenario used (see figure 3.8).

The high costs are primarily caused by a combination of relatively high specific CAPEX and a low number of operating hours. Costs per MWh_e will reduce in case the number of operating hours increase due to more favourable operating conditions for gas fired generation in combination with relatively high prices for natural gas compared to the one for NH_3.

A way to improve the business case is to optimise the use of the NH_3 cracker. At times the Magnum power plant is not operating, H_2 may be produced for other applications, maximizing the potential to generate value from the capital invested in the cracker installation.

As the cost for co-firing are relatively high, it is proposed to develop a demo project aiming at delivering a proof of concept for the conversion of a natural gas fired power plant to full NH_3 firing.

3.2.4.2. Business case Blue 2 (100% NH_3 in one Magnum CCGT unit)

The next logical step after having co-combustion of NH_3 demonstrated in Magnum is to scale-up to full NH_3 combustion. Also in this case the cracking concept is used to convert the NH_3 into H_2 and N_2 before combustion.

In the business case Blue 2 it is assumed that one combined cycle unit is converted to NH_3 firing. To enable full NH_3 -combustion a cracker with a capacity of 200 ton/h NH_3 is needed, additionally investments in the GT are required for new burners. Also investments in unloading and storage infrastructure are needed to accommodate receipt of seagoing NH_3 loaded vessels. A total CAPEX of 246 MEUR (real numbers, base year is 2016) is estimated to be required for business case Blue 2.

As with the business case Blue 1, also for the business case Blue 2 subsidy will be required to compensate for the additional costs of flexible CO_2-free electricity generation. For business case Blue 2 it is assumed that subsidy will be provided for a duration of 15 years.

Unlike the case for Blue 1, the dispatch of the power plant is not driven by the operational costs of operating on natural gas. Main drivers that control the operating hours are the price of the NH_3 and the amount of subsidy provided for each MWhe that is produced.

In the modelling approach taken, the subsidy grant per MWhe will be varied to a level in which the value of the Blue 2 business case equals to the value of the reference case in which the Magnum power plant continues to be operated on natural gas. As a result, the operating hours of the power station will be influenced too, because as long as the combination of the market price of electricity and the subsidy per MWhe produced exceed the variable costs of the power plant (which are largely driven by the NH_3 price), the plant will operate.

Comparable to the Blue 1 business case, two NH_3 price scenarios are considered. In the first scenario a fixed target price of 300 EUR/ton is taken for the entire subsidy period of 15 years. In the second scenario a natural gas indexed NH_3 price is taken. An overview of the main valuation assumptions for the Blue business cases is given in Appendix C.

Based on the analysis performed, it can be concluded that the Blue 2 business case can meet the targeted cost level of 100-150 EUR/MWh(e). When the NH_3 is sourced at a fixed price of 58 EUR/MWhth,LHV, the resulting costs are in the range of 115-125 EUR/MWhe depending on the market price scenario. The Nuon Magnum plant will operate approximately 7000 hours per year, which is a significant increase compared to the case in which the Magnum power plant continues to operate on natural gas and comparable to the operating regime of coal fired power stations (see Figure 3.9).

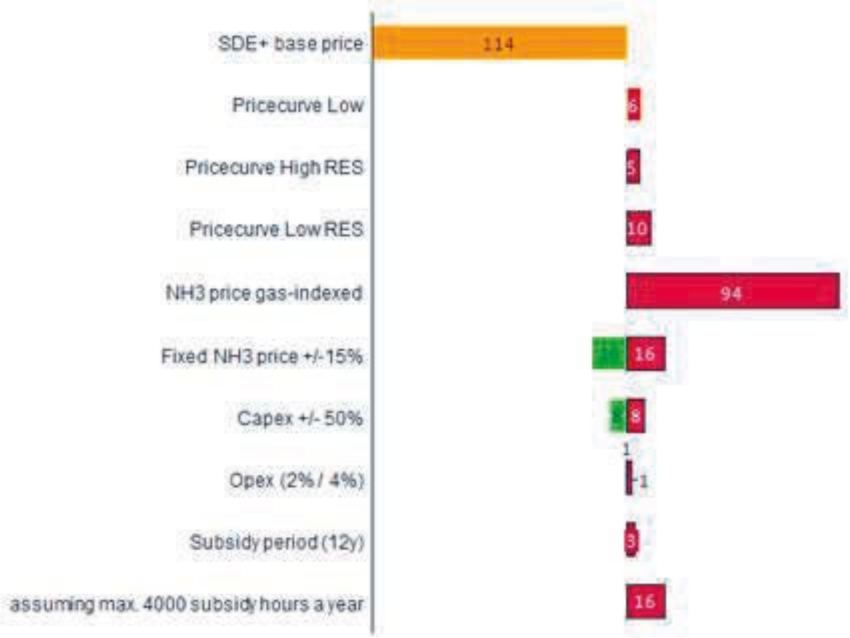

Figure 3.9 Sensitivity analysis business case Blue 2

In the price scenarios where the NH_3 price is indexed to the natural gas price, costs increase to levels of 155-210 EUR/MWh_e depending on the market price scenario used. This is due to the increasing natural gas prices in the outer years in the market price forecasts. The main effect of this increasing NH_3 price is that operating hours of the Magnum power plant will significantly decrease, limiting the potential to earn back the invested capital with subsidies.

The latter sensitivity in Figure 3.9 represents a situation in which only 4000 full-load hours per year are eligible to subsidy. A situation like this is feasible considering the rationale of combusting NH_3. Namely, NH_3 having the ability and being used to fill gaps in the electricity demand, at moments wind and solar are unavailable. Depending on what price curve is used, the additional base amount of subsidy necessary is between 7-20 EUR/MWh.

As with the Blue 1 business case, the business case Blue 2 may be optimized by maximizing the use of the NH_3 cracker. The improvement potential is however more limited compared to the Blue 1 business case due to the relatively high amount of operating hours.

3.2.5 Storing local excess power as NH_3 (BC Yellow)

The business case Yellow is to some extent similar to the business case Red 1, as it is characterized by NH_3 production from intermittent supply of (excess) electricity in combination with low electricity prices.

In the high-RES scenarios of CE Delft, cheap electricity (ca. 0 EUR/MWh_e) is available in 2030 during a significant amount of hours (ca. 3000 hours/year). During these hours there is an opportunity to convert the electricity to H_2 and potentially to NH_3. In line with the conclusions of business case Red 1, the resulting NH_3 costs will be relatively high due to the relatively low load factor in combination with high investment costs in the NH_3 production plant. The business case will become more attractive if the primary response (timescale seconds) and secondary response (timescale quarters of an hour) will be included.

Therefore, next to significant further penetration of variable renewable energy sources (wind and solar) in the electricity system, technological developments aiming at reducing investment costs are required to reach reasonable NH_3 prices, such as low temperature SSAS. The combination of SSAS and the availability of cheap electricity during ca. 3000 hours/year should lead to a reasonable cost level for NH_3 (approx. 325-350 EUR/ton).

It should further be noted that a market mechanism or subsidy regime for energy storage needs to be established to make a viable business case for the Yellow case. A substantial higher price for CO_2 emissions under the ETS-system has similar positive effects on the business cases.

3.2.6 Conclusions

It has been demonstrated that import and or storage of renewable electricity is expected to be required to meet the future CO_2 targets for the power generation sector. NH_3 provides a feasible new option for import with the current technology status when it is produced from natural gas with CCS or from base load renewable electricity like geothermal or hydro. For importing or storing intermitted renewable electricity such as remote solar or local wind, further technological developments are required like low cost electrolysers and low temperature SSAS.

Limited co-firing of NH_3 in Nuon Magnum is economically not attractive due to the limited number of operating hours of the NH_3 cracker. If the cracker can be operated continuously for other H_2 consumers this might change. 100% NH_3 firing is economically feasible with an SDE+ type of subsidy and when sourcing of NH_3 against a cost around 300 EUR/ton.

A key question is to what extent the produced H_2 will actually be shifted to NH_3 in case of excess electricity. Other applications for produced H_2 (e.g. use in industry or in the transportation sector) may be available to use H_2 generated during shorter periods in which excess electricity volumes are available. Shifting towards NH_3 and subsequent conversion back into electricity may not be the preferred option for short term energy storage.

Next to the techno-economical evaluation also safety and environmental impact are relevant as well as the public perception. Although assessed as feasible at this moment, these elements will materialize during the permitting process.

As a final remark, in case synergies may be realised with other initiatives related to development of an H_2 infrastructure in The Netherlands (e.g. Northern Innovation Board), the business cases may be improved. This should be explored further.

3.3 Goeree-Overflakkee case

3.3.1 Rationale

On the island of Goeree-Overflakkee the local renewable electricity production from wind and solar is rapidly increasing. Also a tidal electricity production facility is under investigation. This leads to a net amount of electricity production that exceeds the electricity demand of the island itself.

Figure 3.10 Renewable production as is and foreseen on Goeree-Overflakkee

Therefore grid operator Stedin Netbeheer has during the past years invested more than 100 MEUR in increasing the transport and distribution capacity of the electricity grid in order to be able to transport electricity off the island.

Figure 3.11 The distribution grid of Stedin Netbeheer

The low voltage distribution grid of Stedin Netbeheer has been modified to accommodate for all domestic demand as well as current wind and solar production on the island. The wind and solar production capacity on the island already exceeds the net electricity demand capacity at this moment, which peaks at around 30 MW_e. For the coming years robustness of the distribution grid is secured. In Figure 3.11 the distribution grid is shown.

The high voltage transportation grid of Stedin Netbeheer shows only two locations, Middelharnis and Ooltgensplaat, where the island is connected to the mainland grid. Capacities of these two connections have already been increased over the past years in order to accommodate for the local renewable production. In Figure 3.12 the high voltage transportation grid is shown.

Figure 3.12 The high voltage transportation grid of Stedin Netbeheer.

The total installed capacity of local renewable electricity is expected to increase to a total amount of 300 MW_e 2020. Figure 3.13 shows the expected growth in load on the grid in the coming years. The increase rate (% growth/year^2) may differ (e.g. the new installed wind and solar entering the grid over time), however the expected total capacity will be achieved.

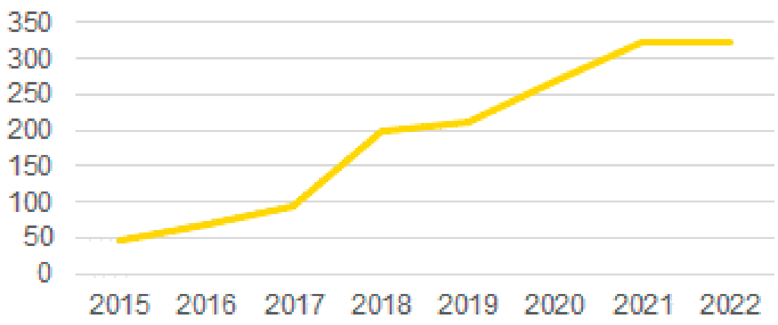

Figure 3.13 Expected load growth in MWe on the Stedin Netbeheer electricity grid

It is foreseen that further grid investments are necessary to be able to accommodate for the further increase in renewable electricity production. These investments are twofold. On the one hand investments in connecting decentralised renewable production sites to the high voltage transportation network in Middelharnis are foreseen. On the other hand further increasing transportation capacity is expected, meaning that for instance investments in the substation at Middelharnis are required. A rough estimate of these investments adds up to a total of 50 MEUR.

To create a more flexible electricity system, several local storage systems, demand side management and conversion technologies e.g. power-to–products are under investigation.

The rationale for this is that electricity that is locally produced could also directly be used and converted into valuable chemical products like NH_3, thus not requiring any grid capacity. This means that investments in local electricity conversion capacity add to grid capacity on the one hand and avoid costly investments in increasing conventional grid capacity on the other hand. This means the important value driver for investing in conversion technology as part of the electricity grid originates from avoided conventional grid capacity investments. Apart from this incentive, the renewable character of the NH_3 product as well as the possibility for grid balancing services should also be valued. In this case the grid balancing services are taken into account, but are not given any value.

3.3.2 Value chain

The generic value chain for the Goeree-Overflakkee case, where power-to-ammonia is being used to create flexible electricity conversion capacity is depicted in Figure 3.14.

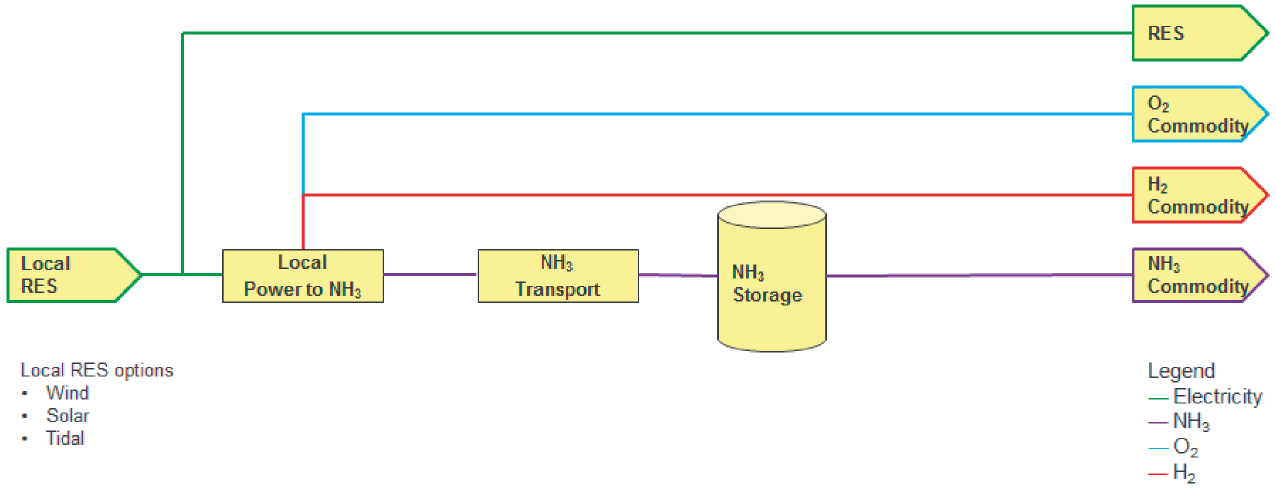

Figure 3.14 Generic value chain

In this study, we have focused on the case where local RES is converted to NH_3 and being transported to storage. Individual streams as O_2 and H_2 from RES are not taken into account.

For the Goeree-Overflakkee case we have distinguished three different value chains, differing in the location as well as the connection to the electricity grid.

1. **Tidal power production facility Brouwersdam**
   Producing NH_3 with the power that is available from the tidal power facility that is envisaged to be located in the Brouwersdam. The installed capacity of the tidal power facility is 25 MWe and there is no connection to the grid.

2. **Direct NH_3 production at the grid substation Middelharnis**
   Producing NH_3 at the distribution station near Middelharnis. At this site a number of power cables from various wind and solar production facilities meet. Power from the grid is also available at this site. A modular set-up approach of the NH_3 production units will be chosen. The maximum power that can be used is 50 MWe. The NH_3 production facility has a demand of 40 MWe.

3. **Stand alone.**
   Producing NH_3 at a "stand alone" wind park. In this case there will be a more fluctuating and less predictable supply of power compared to the situation at Middelharnis. Moreover, there is no possibility to use power from the grid.

Figure 3.15: The geographical locations of the three cases at Goeree-Overflakkee

In all the three cases the NH_3 that is produced will need relatively small local storage capacity before it is transported. After production, direct transportation with trucks to a dedicated NH_3 storage (e.g. the OCI NH_3 terminal in Rotterdam) facility is required.

3.3.3 Technical assessment per case

3.3.3.1. Case 1 - Tidal power production facility Brouwersdam

In the Brouwersdam, a dam that fully separates the estuary delta from the sea, a tidal power production facility is under development. The project not only focusses on the production of renewable electricity, it also serves other purposes. The facility offers the possibility to regulate the water height in the estuary delta, thus increasing safety levels for the inhabitants. It also enhances the environmental situation by bringing back fresh salty water into the presently brackish estuary delta water system. Apart from all these elements, a tidal production facility in an estuary delta system is a new and world class innovative system creating lots of knowledge and economic exportable value.

Figure 3.16 The tidal production facility in the Brouwersdam

In Figure 3.16 the tidal power production facility is shown. Production of NH_3 from electricity is carried out next to the tidal production facility making use of water electrolysis combined with the Haber-Bosch conventional NH_3 synthesis process.

Since the output profiles of the production facility are not yet known, the following assumptions have been made:

- In a time period of 24 hours there are 4 periods of 1 hour that there is no tidal current so in these periods no power can be generated.
- In the 4 time periods of 5 hours that there is current there will be assumed an (almost) constant yield.
- In the time periods that there is no tidal current the NH_3 production must be maintained at a level of min. 25% of the production capacity. This is necessary because complete shut down and start up put too heavy a load on the installation and also there will be some loss of product. The consequence is that a certain amount of H_2 has to be stored to overcome these time periods and keep the NH_3 production facility running.
- The NH_3 production unit has a capacity of 20.000 ton/year. Such an installation fits perfectly to the available amount of power.
- The specific electric power consumption of the NH_3 production unit ranges from 12 to 15 MWh_e/ton NH_3. Because there is no grid connection, no power can be taken from the grid when the tidal facility is not generating power. One option is to use a part of the H_2 that is being produced by electrolysis. Power can then be generated by a fuel cell. Any solution making use of a separate power generator which needs fossil fuel will not be sustainable and will therefore not be considered.

The simplified electricity production profile from the tidal power plant is shown in the figure below.

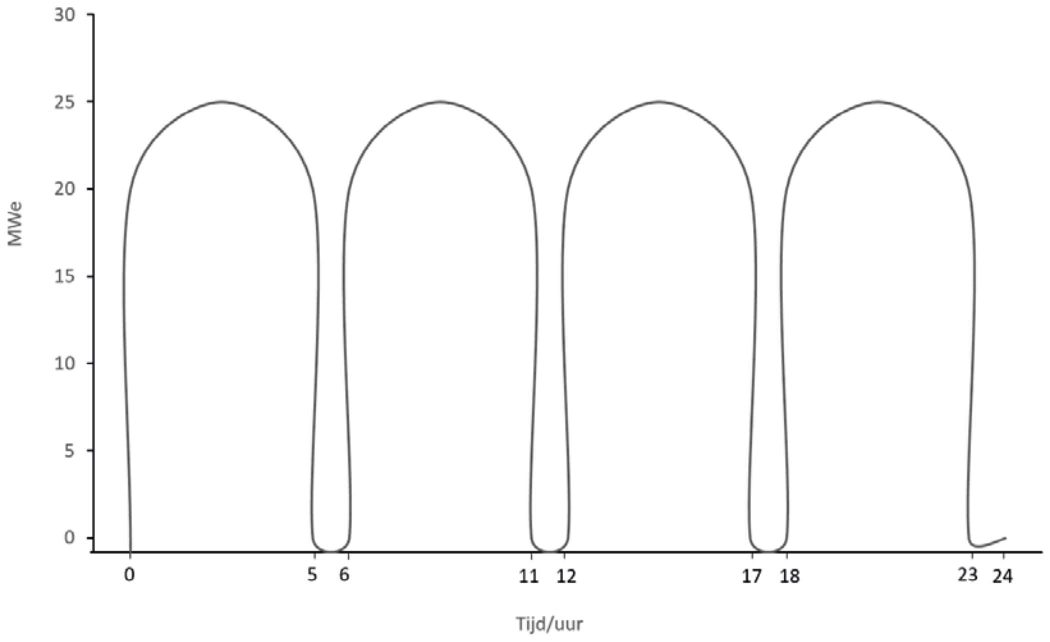

Figure 3.17 Assumed electricity production profile from the tidal production facility in the Brouwersdam.

The assumption is that during the 5 hour periods 20 to 25 MWe is generated. In principle, this will be all converted into H_2. The equipment can be primarily alkaline electrolysers and for a small part PEM electrolysers due to the fact that there is a fairly continuous power supply available. PEM electrolysers are very flexible in following load changes, which is obviously not needed. For this application therefore relatively cheap alkaline electrolysers can be chosen.

The installed NH_3 production has a maximum production capacity of 20.000 tons/year, e.g. 2.3 tons/h. This equals to a H_2 need of 410 kg/h. To produce this maximum amount of NH_3 there is a continuous demand of 20 MWe electric power. This figure is based on the expectation that 1 MWe continuously available power equals 1000 tons per year of NH_3 production.

In the time periods of 1 hour that there is no power generated by the tidal facility, the NH_3 production capacity will be reduced to 25% of maximum capacity. Thus, lowered until approximately 600 kg/h NH_3 requiring 100 kg/hour of H_2.

To be able to cover the 1-hour time periods there must be at least 100 kg of H_2 available, meaning that a H_2 storage facility with a capacity of 150 to 200 kg is required. This H_2 can be produced when the tidal power facility generates more than 20 MWe. In the 5 hours during which 20 to 25 MWe electric power is generated there will be sufficient power production, typically 2 to 3 MWe in this period, to produce the required additional 100 kg of H_2.

The total amount of NH_3 produced will be approximately 5/6*20.000+1/6*5.000=17.500 tons of NH_3 per year.

The full NH_3 synthesis production process has been schematically depicted below.

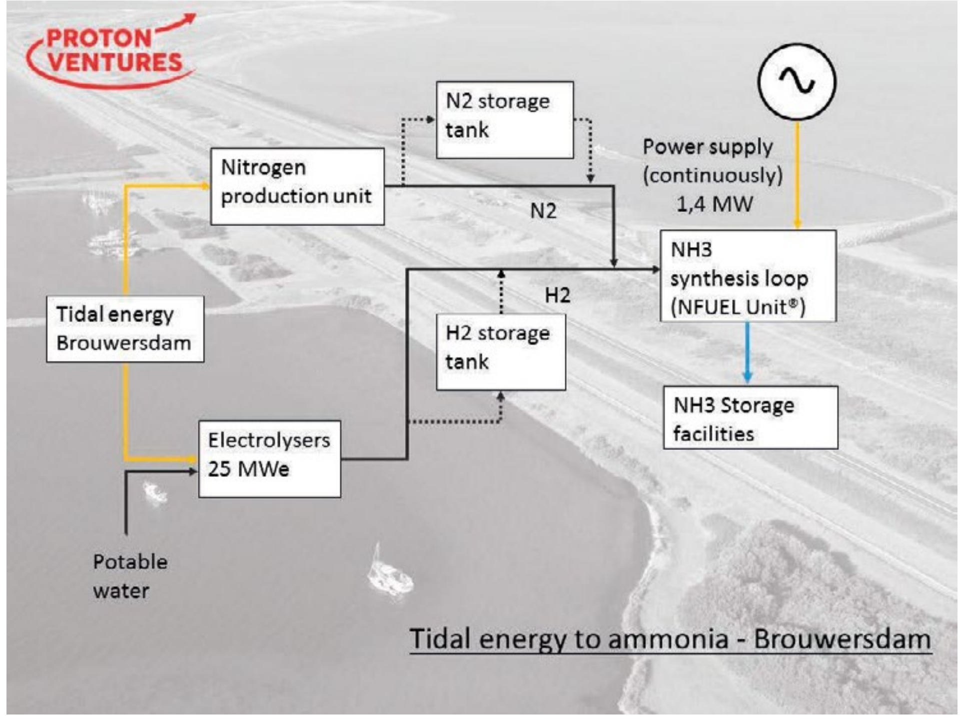

Figure 3.18 NH_3 production facility next to the tidal electricity production facility in the Brouwersdam.

In summary the P2A plant features:

- A tidal production facility with 25 MWe installed capacity
- Haber-Bosch NH_3 production unit with a capacity of 20.000 ton/year NH_3
- A fuel cell to continue power supply when the tidal facility is not producing
- Storage facility of 100 to 150 kg H_2
- Installed capacity of electrolysis units: 25 MWe
- Total NH_3 production: 17.500 ton per year

3.3.3.2. Case 2: Direct at the grid substation Middelharnis

At the grid substation in Middelharnis further investments will be needed to create substantial capacity allowing transport of all renewable power produced from solar and wind from the island. Stedin has investigated and engineered the needed infrastructural modifications to increase transportation capacity. At this moment the investments needed by Stedin are estimated at 12 MEUR. Figure 3.19 shows the needed infrastructural adjustments.

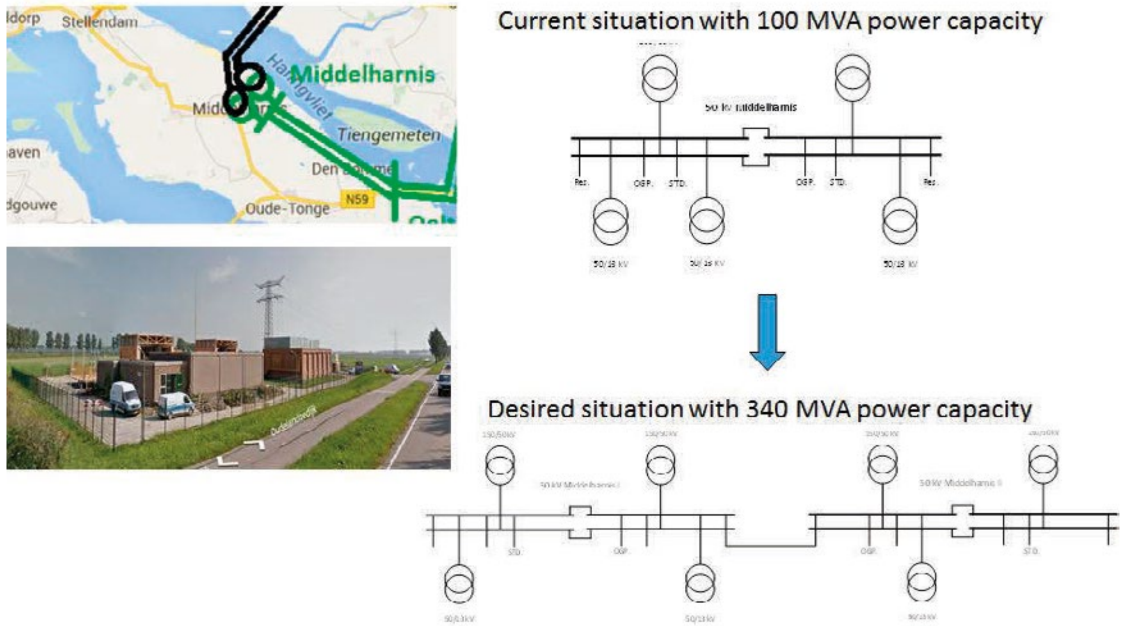

Figure 3.19 Infrastructural adjustments needed at the substation in Middelharnis to create more transport capacity.

Production of NH_3 from electricity is carried out next to the substation making use of the Haber-Bosch conventional NH_3 synthesis process.

The P2A production facility is constantly operating at full 40 MWe capacity. When at a certain moment there is no or not enough wind and/or sun power available the electricity will be extracted from the grid. The part of the NH_3 produced with sustainable electricity from the grid will be covered with green certificates which proving that the NH_3 is being produced without CO_2 emissions. It shall be considered that NH_3 produced by the P2A plant consuming grey electricity will result in specific CO_2-emissions of 6 ton CO_2 per ton NH_3 where the conventional SMR based process result in specific emissions of 1.8 ton CO_2 per ton NH_3. This implies that for every ton NH_3 produced from grey electricity at least 2 tons of “green” NH_3 must be produced to reach a break-even point on CO_2-emissions.

The full NH_3 synthesis production process has been schematically depicted in Figure 3.20.

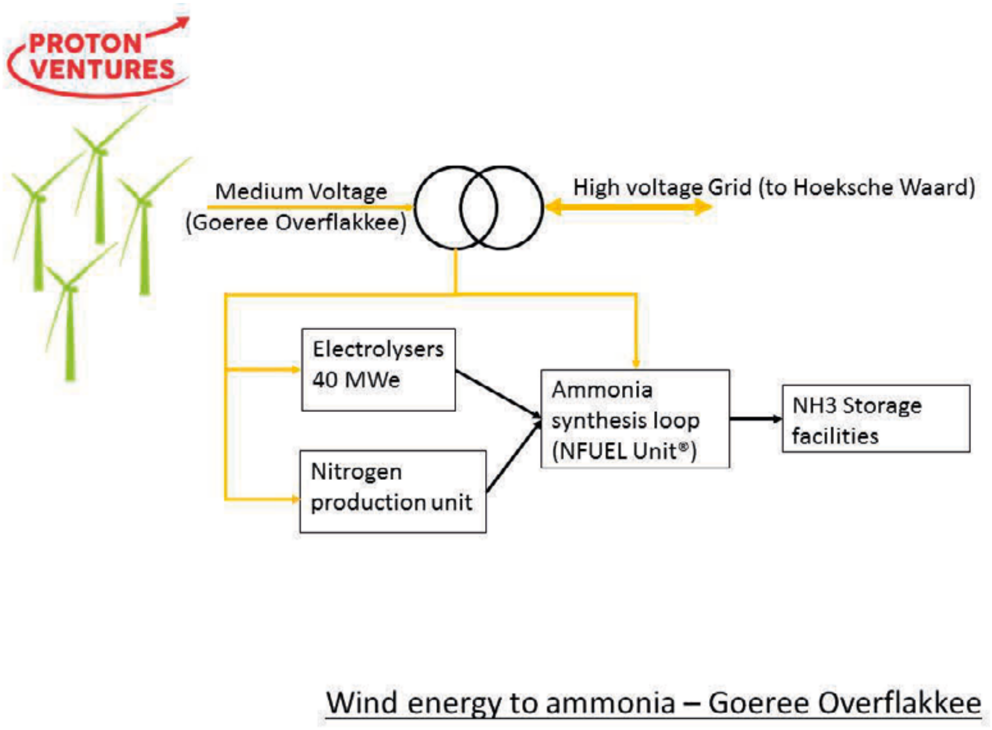

Figure 3.20: Full ammonia synthesis production process at the substation in Middelharnis.

In summary the P2A plant features:

- Production facility with 40 MW_e installed capacity
- Installed capacity of electrolysis units is 40 MW_e
- Haber-Bosch NH_3 production unit with a capacity of 40.000 ton/year NH_3
- Total NH_3 production: 40.000 ton/year

3.3.3.3. Case 3: Stand alone

Production of NH_3 from electricity, making use of the Haber-Bosch conventional NH_3 synthesis process, is carried out next to a decentralised wind or solar production facility on the island. No grid connection is available, therefore all the electricity that is produced, will be converted into NH_3.

When a NH_3 production unit will be placed near a “stand alone” wind or solar park it is crucial to have good indications for the wind profiles as well as the solar PV production analyses. In this situation there are periods during which insufficient or no wind or solar available to keep the P2A plant in operation. In order to avoid a shutdown of the plant H_2 storage of sufficient size is needed to produce a certain period on a minimum level of 25% capacity.

The capacity for H_2 storage needed to overcome the time periods when there is no electricity production is substantial. This is heavily impacting the business case for case 3. So it is concluded that, from a business economics point of view, it is not feasible to invest in a P2A production facility directly connected to a wind or solar production facility. Case 3 will therefore not further be analysed.

3.3.4 Business case assessment

3.3.4.1. Application of the NH_3 produced

In both case 1 and case 2 the production costs for NH_3, based on CAPEX and OPEX have been calculated including storage and transport of the NH_3.

The most attractive option is to transport the NH_3 produced at Goeree-Overflakkee by truck to the OCI NH_3 terminal at Rotterdam Europoort. Every day approximately 50 tons of NH_3 needs to be transported. This means two or three trucks per day. An estimation of the costs of storage and transportation results in 35 EUR per ton NH_3.

An interesting alternative might be to convert the produced NH_3 on site with CO_2 into urea. This urea can be used locally so the need for transport of NH_3 will be eliminated. The produced urea can be used as a “green” fertilizer on Goeree-Overflakkee. Another application is as a $DeNO_x$ agent (tradename AdBlue) to prevent the emission of NO_x in road transportation. For a “small” urea production unit that fits with the quantity of NH_3 produced the investment is estimated at approximately 20 MEUR. However, a CO_2 source is not available at Goeree-Overflakkee, it must be transported by truck in order to convert the NH_3 into urea directly on the island.

3.3.4.2. Case 1 - Tidal power production facility Brouwersdam

An important aspect in the total business case will be the avoided investment costs for a full grid connection. These costs need to be calculated and depend on the distance to the connection point. A first and very rough estimation is 15 MEUR. The estimated investment in the P2A facility is 42 MEUR, so the net investment taking into account the avoided grid connection is about 27 MEUR.

Summary of revenues estimates:

- Current market price of “fossil” NH_3 is 400 EUR/ton (high estimate).
- Yearly revenue: 17.500 * 400 = 7 MEUR/year

Summary of operational costs

- Feedstock costs
- Maintenance costs
- Labor costs

For the electricity price the current APX-value have been used.

- When a price of 35 EUR/MWhe (current APX-value) has to be paid then the feedstock costs at a continuous production of 20 MWe and 8500 operating hours will be: 20 * 8500 * 35 = 6 MEUR/year.
- Maintenance costs are estimated 2% of the investment, this means yearly costs of 0.02 * 50 MEUR = 1 MEUR/year.
- The labour costs will yearly be less than 0.5 MEUR with the assumption that there’s no need for continuous operator attendance.
- This adds up to a total operational cost (OPEX) of 7,5 MEUR/year (+/- 30%)

With all assumptions being made, it is clearly seen that it is not possible to produce NH_3 against market-based prices when the power price is at 35 EUR/MWhe. We do not even take CAPEX into account. The yearly OPEX is higher than the expected yearly revenues (negative marginal spread). The cost price of NH_3 including depreciation of the production unit (CAPEX) and the operational costs, simply is too high. Mitigations and different assumptions as well as incorporating other value drivers will be needed in order to create an attractive business case.

3.3.4.3. Case 2: Direct at the grid substation Middelharnis

Summary cost estimates for converting 40 MWe power continuously into NH_3:

- 20 MWe PEM electrolyser units: 24 MEUR
- NH_3 production unit (including skids and connections): 15 MEUR
- Engineering and unforeseen: 3 MEUR
- This adds up to a total investment (CAPEX) of 42 MEUR (+/- 15%)
- The needed 40 MWe installation means a duplication of installation and is estimated at 78 EUR.

Summary of operational costs:

- An assumption is made that the production costs of the (wind) energy is made according to the CE scenarios for electricity pricing
- OPEX is calculated between 2,5 – 3% from CAPEX
- Avoided costs for grid capacity increase 12 MEUR is deducted from the total CAPEX

For the different technologies to produce H_2 (PEM, Battolyser or SOFC) or directly NH_3 (SSAS) the business cases have been developed, taking the electricity pricing scenarios for CE Delft into account. The calculated parameters are the production costs of NH_3. H_2 production from PEM electrolysis is the only feasible option at this moment. The other technologies are not sufficiently mature yet to qualify for selection. In the two tables below for two different years, 2023 and 2030, the production costs of NH_3 are shown. The CAPEX of the battolyzer and SSAS for 2023 and for 2030 is based on information of TU Delft.

				NH_3 prices	[EUR/t]
Case	CAPEX [MEUR]	OPEX [MEUR/yr]	Load factor [-]	Low Fuel	High Fuel
PEM	78,1	2,2	0,9	587	756
Batt	63,5	1,8	0,9	573	757
SOFC	90,9	2,3	0,9	463	588
SSAS	80,4	2,1	0,9	632	813
Reference				414	581

Table 3.3 - Case: $40MW_e$, 12 MEUR avoided cost, 10 years depreciation, 2023

				NH_3 prices[EUR/t]			
Case	**CAPEX [MEUR]**	**OPEX [MEUR/yr]**	**Load factor [-]**	**Low Fuel**	**High Fuel**	**Low Fuel - High RES**	**High Fuel - High RES**
PEM	63,4	1,9	0,9	571	791	490	659
Batt	54,4	1,6	0,9	578	818	489	675
SOFC	72,1	1,9	0,9	438	598	379	502
SSAS	61,6	1,7	0,9	598	833	511	692
Reference				424	629	424	629

Table 3.4 - Case: 40MWe, 12 MEUR avoided cost, 10 years depreciation, 2030

The reference prices for NH_3 have been estimated, based on historical relations between gas prices and NH_3 prices in NW-Europe market price of “fossil” NH_3 and is between 200 – 400 EUR/ton, depending on the source.

Mitigations and different assumptions as well as incorporating other value drivers will be needed in order to create an attractive business case. Possibilities are:

- Lower input electricity prices that might originate from attractive long term power purchase agreements with renewable production facilities.
- Lower estimates for CAPEX as well as OPEX after detailed optimisation and negotiating with technology providers.
- A higher market value for “green” NH_3 compared to the “fossil based” NH_3 commodity price. This higher market value can only be achieved in selected value chains that can afford this at this moment.
- Most important, the avoided costs for all investments on the substation infrastructure as well as on the high voltage grid connection (TenneT) that might be allocated to the P2A business case.
- A substantial attribution to the business case from a rising CO_2 penalty on competing fossil NH_3 leading to higher competitiveness for “green” NH_3.

3.3.5 Conclusions

Conclusions are drawn from the case where PEM electrolysis is applied. The following conclusions have been reached:

- For all of the three cases that have been studied in principle no positive business case for the production of NH_3 from electricity can be achieved at this moment. This business case consists of CAPEX, OPEX and a depreciation period of 10 years. The case where NH_3 is produced direct at the grid substation in Middelharnis has appeared most promising. The other two cases are less interesting due to the fact that the intermittent production of renewable electricity implies lower utilisation of the installed assets and the need for larger and costly storage facilities.

- Avoided grid investment in the case where NH_3 is produced directly at the grid substation in Middelharnis are highest. Even when this is taken into account, the business case is not attractive from a financial point of view. However from a societal point of view, this case is most promising because investments in the grid are being diverted to support a new sustainable initiative also offering new economic potential. Investments in storage technologies are required anyway to accommodate the increasing renewable electricity production capacity.

- Different scenarios for future electricity prices show a great variety in the outcome for the NH_3 price from business cases for the three different cases. Only for the business case directly at the grid substation in Middelharnis the scenarios are used. The other two cases have not appeared feasible due to reasons mentioned above.

- Apart from the expected lower cost for electrolyser technology, other potential upsides for the business case can be found in:
    - offering specific grid services by the P2A plant,
    - contributing additional value from value chains that reward the zero emission character of NH_3,
    - accounting for a rising CO_2 penalty on competing existing technologies based on fossil resources

Some additional remarks:

- In The Netherlands the local grid operators, so called Distribution System Operators, are only allowed to transport energy under a regulated regime. This regulated task is being coordinated by the ACM. Investment made in conversion technology can be done by the non-regulated part of these grid operators. The market model that applies is that these non-regulated entities invest in conversion and offer conversion capacity to the market. This allows the grid operator to increase flexibility in the electricity grid whilst legally complying to their task.

- Stedin Infradiensten is the non-regulated part of Stedin Grid operator. The market model that applies in all cases is being depicted in Figure 3.21

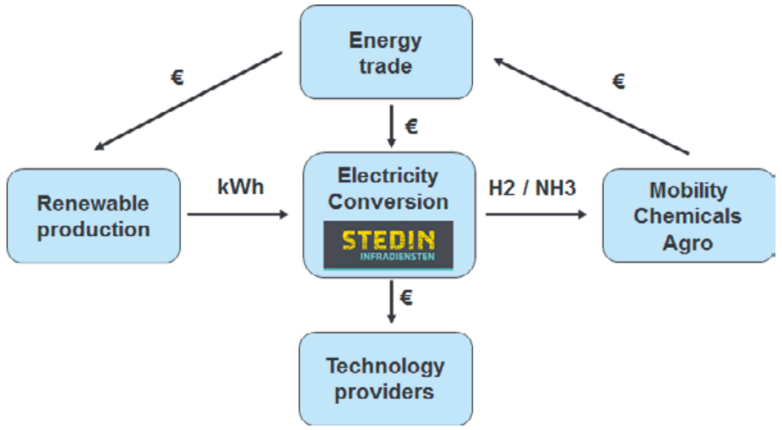

Figure 3.21 Stedin Infradiensten market model

- Safety and security for deployment of P2A is an important issue. This issue is covered in Appendix A in this report

- Local acceptance for deployment of P2A is crucial. The local attitude on Goeree-Overflakkee with respect to new and sustainable initiatives is very positive. Because the local renewable production of electricity is substantial, both inhabitants and government are used to transitional thinking and all the aspects related to this. P2A is a technology that offers sustainable benefits combined with the positive financial elements of creating jobs and economic growth. This is highly appreciated on the island.

- P2A systems in the range of up to 50 MW_e systems can play an important role as a flexibility option for the energy grid in terms of energy storage. However, the most important prerequisite for choosing P2A is that the avoided grid investments are substantial enough to compensate for the negative business case (at this moment).

- Offering specific grid services with the P2A installation like primary and secondary response, are to be taken into account and create substantial additional value. Although not fixed, this value can be added in the business case.

- The best locations to install a P2A facility are those locations where substantial grid investments are foreseen in The Netherlands. These are:
    - the specific areas where lots of newly installed wind energy is started to being fed into the grid. These areas are known for the coming years as the offshore wind farms are selected and the places where the offshore electricity grid enters the onshore grid are known (e.g. IJmuiden, Borssele, Eemshaven). Note that at this moment the potential of P2A as a storage technology is under investigation in the range of more than 1000 MW_e.
    - areas where substantial repowering of existing wind is taking place (e.g. Maasvlakte, Flevopolder)
    - the specific areas where lots of newly installed solar PV is entering the grid. These areas are little known as they arise
- P2A seems an attractive technology to apply in cases where a choice has to be made to transport electricity from renewable production facilities

- Presently, NH_3 can only be produced on Goeree-Overflakkee when the higher production costs of this medium can be allocated to its zero emission "green" character. This means that the NH_3 can only be put in value chains that allow for a higher NH_3 price and award the "green" locally produced character. It now seems interesting to further investigate the potential for this NH_3 as a building block for zero-emission fertilizers such as ammonium nitrate.

- A consortium of parties involved in the value chain of zero emission ammonium nitrate should be constructed to exploit the outcome of this P2A study. Parties involved in renewable electricity production on Goeree-Overflakkee towards end-users of products that use ammonium nitrate as a fertilizer should join forces to investigate "is it real?" , "can we win?" , and "is it worth winning?"

- P2A as a new way to convert local renewable electricity into a valuable energy carrier can avoid grid investments and can be applied at increasing production capacities in the near future. This means that not only the investigated case at Goeree-Overflakkee might seem interesting, also in other areas where substantial grid investments are needed the P2A technology might be interesting and worthwhile to investigate.

- It appears very attractive to determine the feasibility of P2A when including the high voltage grid investments that Tennet foresees in the short and medium term future. These high voltage grid investments are very costly (billions of euros) and take long lead times (over 10 years)

- Higher penalties for CO_2 emitting industries that produce NH_3 in The Netherlands from fossil gas (OCI and Yara), could result in a fast deployment of P2A to substitute production, unless this industry is forced to stop production in The Netherlands.

3.4 OCI Nitrogen

3.4.1 Rationale

In parallel to the business cases of Nuon in the Eemshaven and Stedin at Goeree-Overflakkee, a third business case has been developed for a small scale pilot P2A plant at OCI Nitrogen, either at their site in Geleen or in Europoort. At both sites the infrastructure for chemical processes and NH_3 is present. This will reduce the investment in utilities and handling as well as reducing the lead time, costs and complexity of the permits.

3.4.2 Value chain

A small scale unit (stand alone, electrolyser based, 20 kton NH_3 production per year based on 8000 operating hours) has been selected because this would be an optimal size for testing all the effects of discontinuous operation, and where product volumes are still significant. Lessons learned from this installation could be transferred to full scale P2A plants.

3.4.3 Business case structure

The optimal strategy for operating an electrolyser based NH_3 plant depends on two main factors: fixed and variable costs. The fixes costs include maintenance, wages, land lease, grid connections, depreciation and interest. Variable costs consist mainly of electricity (and some nitrogen and water). If the plant can be operated only during the hours when electricity is cheapest (based on day-ahead market), variable costs can be minimised. When calculating the production costs of NH_3 the number of hours the plant is operating is affecting both factors: more hours means less fixed costs per ton, but the average electricity price also rises.

The business case has been calculated using the following figures:

- The investment is in the magnitude of 30 MEUR, based on an estimate by Proton Ventures.
- The lifetime of PEM-electrolysers is around 10 years, where the NH_3 synthesis plant will be depreciated in 15 years.
- Electricity consumption and other variable costs (demi water, air etc are mainly energy driven) will be equivalent to 10.5 MWh_e/ton NH_3.
- Production will be linear to the operating hours, with 20 kton/year based on 8000 operational hours per year
- Fixed cost (2% of the capex), depreciation (15 years) and interest (7% WACC) together will be around 5 MEUR/year.

In the figures below, the relation between number of operational hours and the fixed and variable costs are given. The lowest cost-price will be achieved at different operating hours for each price curve. In the near future and lower RES scenario’s, the installation should be running almost continuously to achieve the lowest cost price. In the high RES scenario’s the utilization will drop to 50-60%, following the oversupply and preventing curtailment of RES.

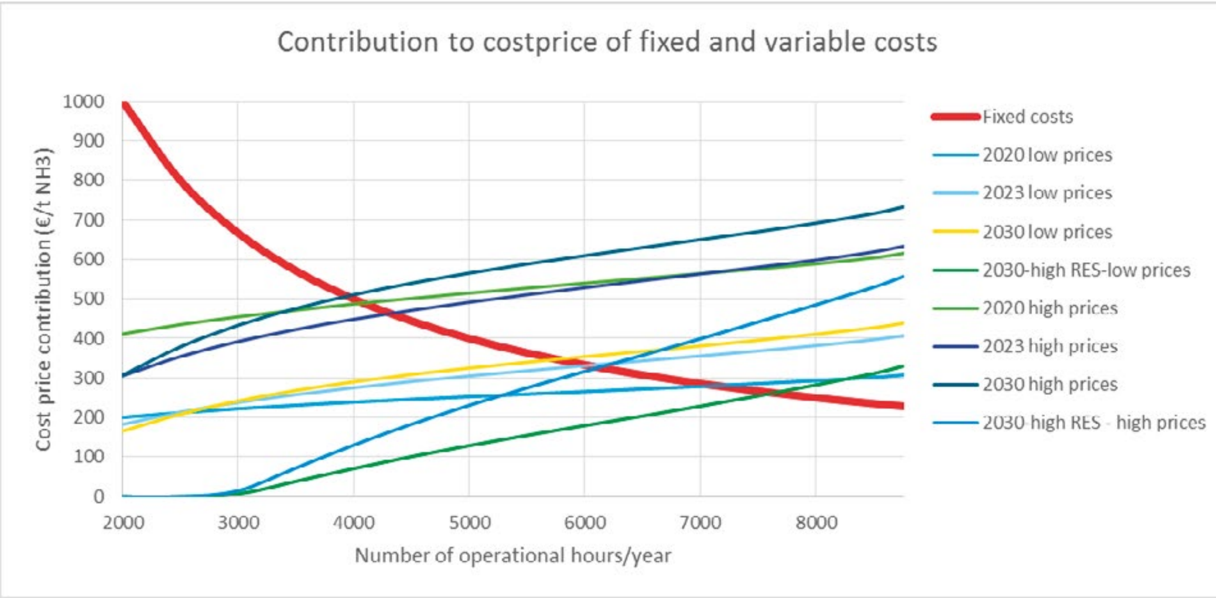

Figure 3.22 Effects of operational hours on fixed and variable costs

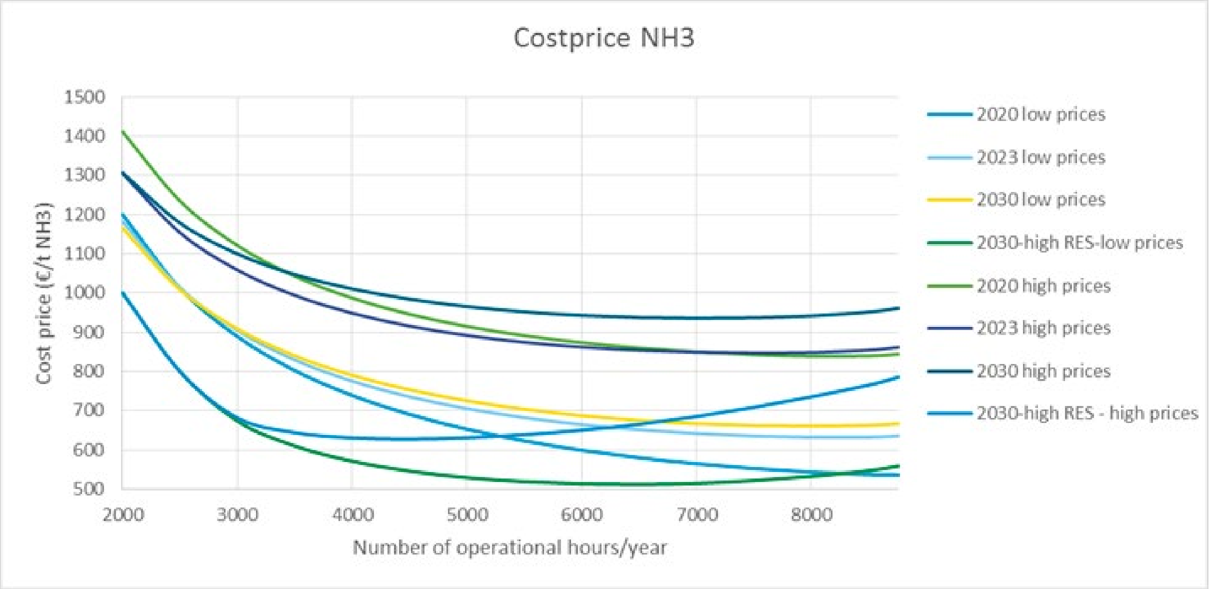

Figure 3.23 Effects of operational hours on integral cost price of NH_3

As market prices for NH_3 are generally well below 500 EUR/ton, it is not yet possible to produce NH_3 at a profitable level for OCI Nitrogen. The gap with current market prices, around 300 EUR/ton, is too big to bridge.

3.4.4 Conclusions

Comparing these cost prices to the current market price of NH_3, in none of the cases a profit can be made. However for the 2030 high renewable energy scenario differences are small. And with some further optimisation of the operational hours the break-even point might be reached.

However, if the investment could be reduced significantly and/or the pricing of renewable NH_3 is significantly higher, this electrification route could be profitable before 2030. Innovations on the electrolyser markets such as the battolyser also have a great potential.

Other ways to increase profitability could be to act on both day-ahead-market and imbalance market, to include avoided investment (e.g. in power grid) and to find subsidy schemes (like SDE+/EIA) or alternative attractive financing models.

In order to reduce the CO_2 footprint of this NH_3, compared to conventional NH_3, the electricity has to come from a CO_2-free source. When using CO_2 electricity from non-renewable energy sources the CO_2 footprint is actually much higher due to the efficiency loss when producing electricity. Taking power produced from natural gas with a specific CO_2 emission of 360 kg/MWh_e would result in a specific CO_2 emission of approximately 3.6 ton per ton NH_3 while conventional SMR based NH_3 production from natural gas would result in 1.8 ton CO_2 per ton NH_3.

In this analysis the number of operational hours has been optimised to reduce the effects of CAPEX. Except for the 2030 high renewable energy scenario (RES), the availability of hours with abundant RES will be insufficient to compensate the higher CO_2 footprint of the other hours.

4. Conclusions and next steps

Conclusions

1. The production of NH_3 from renewable electricity from The Netherlands is on the short term economically not attractive. The main reasons are a limited availability of cheap (< 15 EUR/MWhe) renewable electricity resulting in a limited number of operating hours in combination with high CAPEX. The investment is mainly determined by the electrolysers for the production of H_2.

2. The business case to produce NH_3 with renewable energy sources (RES) in 2030 in North West Europe can be profitable in a high RES scenario when the production is done at times when prices for RES are low due to high supply and low demand. This CO_2 free NH_3, used as a means of energy storage, can be used to produce electricity at times when supply of RES is low and demand is high. The storage can be used on a time scale of weeks and even months. The economic feasibility depends on a lot of factors, but in particular also on the business model for such a storage.

3. The business case to produce CO_2 free NH_3 in countries where renewable electricity is abundantly available can be profitable if sufficient operating hours are possible. This is for example the case for geothermal and hydro applications. Also the production of CO_2-neutral NH_3 from natural gas in combination with Carbon Capture and Storage (CCS) is a potentially interesting route.

4. Solar stand alone in desert type areas is predictable but will result in too little operating hours to be profitable with the currently expected CAPEX levels. This can be resolved if a combination with other renewables sources can be realized and/or existing storage facilities are present.

5. The analysis of production costs of the electrochemical production of NH_3 shows that electrolysers determine the cost-price. The lowest overall production costs for electrolyser-based NH_3 in North West Europe result at relatively high number of operational hours per year, depending on the power market scenario (7000-8000 hours in most scenarios, ~4000 hours or less in the high RES 2030 scenario). With electrolysis being a major part of the electrification of the process industry, additional research towards reduction of the production costs is needed. A target for cost reduction is 70% of the current base price of 1000 EUR/kW.

6. NH_3 produced from renewable electricity can be used in the future as sustainable alternative for NH_3 produced with natural gas. It can be a building block for the chemical industry looking for ways to make their products more sustainable. In order to become competitive, green NH_3 needs lower production costs, and/or a premium price as green NH_3, and/or higher costs for CO_2 emission and/or governmental regulation. Whether the market price of "green" NH_3 can be (much) higher than "normal" NH_3 has to be investigated.

7. NH_3 can be used as a fuel in a power station by cracking the NH_3 into H_2 and N_2 prior to combustion in gas turbines. This route is attractive because CO_2-free NH_3 can be used to

produce power and it can be sold as CO_2-free H_2 as an alternative for non-renewable H_2. This enables a close connection between electricity generation and a H_2-economy for chemical industry and transportation. Cracking NH_3 is nowadays only done on a small scale. The technology for large scale cracking must be developed in the coming years. Time to market for large scale applications is estimated to be between 5 and 10 years. Using CO_2-free NH_3 as fuel will require an SDE+ type of support scheme.

8. Meeting the 2030 and later targets for CO_2-requires large scale storage and/or import (TWh scale) of renewable electricity. NH_3 enables both.

9. Concerning the production of NH_3 in the Stedin case on Goeree-Overflakkee the produced “green” NH_3 will be sold on the market. One of the most economically interesting options for distributing the NH_3 is to use the OCI Nitrogen terminal in the harbour of Rotterdam. With trucks the NH_3 can be transported to this terminal.

10. An advantage of producing NH_3 with wind and solar power for the grid owners will be lower investments in the grid. If the share of wind and solar power increases without demand side management and without energy storage the investment in strengthening the grid will be substantial. The combination of demand side management and local energy storage (like NH_3 storage) can contribute to the reduction of the necessary investments in the grid.

11. The CO_2-emissions of electrochemically produced NH_3 with renewable electricity are zero. This does not mean that producing NH_3 electrochemically always emits less CO_2 than the current way of production. Producing NH_3 from natural gas by means of SMR results in 1.7-2.1 ton CO_2 per ton NH_3, depending on the technology. If ‘grey’ electricity (currently on average 0.54 ton CO_2/MWhe in The Netherlands) is used to produce NH_3 electrochemically the emissions are around 5.5 ton CO_2 per ton NH_3 based on energy consumption of 10 MWhe per ton NH_3. This is considerably higher than the emissions caused by the production of NH_3 with natural gas.

12. The current ETS system does not provide an incentive for the production of low or no carbon free NH_3. CO_2 prices should be far higher than they are today in order to make NH_3 from renewable electricity competitive. However, due to the global market for NH_3 and the lack of import duties on NH_3 (based) products, such a high CO_2 price would lead to carbon leakage. The production will be done outside the EU from fossil fuels, often using processes with a higher CO_2 footprint. In order to make the CO_2-free NH_3 price competitive, the costs per avoided ton of CO_2 producing NH_3 from renewable electricity is in the range of 75-300 EUR/ton CO_2. The price range mainly depends on two factors: the capital expenditure (CAPEX) in relation to the operational hours and the operational expenditure (OPEX) which will be determined by the price difference between CO_2 free electricity and natural gas including CO_2 emissions costs.

Next Steps

Stedin Goeree-Overflakkee

- On Goeree-Overflakkee the efforts continue to produce NH_3 on a small scale with green energy (wind and sun). The government of Goeree-Overflakkee is interested in the possibilities to use the produced NH_3 (or urea) on the island. This contributes to more sustainability and local employment opportunities but will require a premium to be paid for the green character.
- More research should be done and a pilot for NH_3 synthesis has to be built to see if operation on interval basis is possible.
- The electrolyser technology much become developed for large scale applications including a substantial decrease in the costs.
- Societal acceptance of the local production of NH_3 on the island will be explored more in detail.

Nuon Eemshaven

- Discussions to. realize a SDE-like subsidy for using of CO_2-neutral NH_3 and H_2 as a fuel for electricity production should be initiated.
- A business model including roles and responsibilities needs to be developed with relevant parties for storage of electrical energy.
- Further research should be done to explore the best options to crack NH_3 into H_2 and combust the H_2 in a gas turbine.
- A demo plant should be developed to get experience with the cracking of NH_3 into N_2 and H_2.
- The combustion of H_2 rich gases needs to be explored with gas turbine manufacturers, using their experiences from the past and development programs if applicable.
- More research is needed to find out where CO_2-neutral NH_3 can be produced on large scale with low production costs.

AkzoNobel

- AkzoNobel will continue to explore opportunities to better valorize the H_2 that it currently produces as a byproduct and is also investigating whether extension of its electrolysis activities into water electrolysis would be attractive. One of the options for the valorization of the H_2 would be NH_3 production. AkzoNobel does not intend to be the investor or operator of a future NH_3 production plant, but would be interested to provide such a plant with H_2 and purchase part of the produced NH_3 as raw material for its processes. In the steps towards such a future plant, AkzoNobel would be willing to take part in a consortium that aims to demonstrate the technology on a significant scale, especially if this demonstration would be carried out in Delfzijl.

R&D

- The analysis of production costs of the electrochemical production of NH_3 shows that the investment costs of the electrolysers are dominant. The expectation is that the coming years the cost price of large electrolysers will decrease. Also new type of electrolysers are being developed. With electrolysis being a major part of the electrification of the process industry, additional research towards reduction of the electrolyser costs is needed. The required R&D steps are listed below:
    - Continued R&D on battolyser technology, electrolysis and NH_3 synthesis technology. The cost target should be 300 EUR/kW_e for the electrolyser producing H_2.

- H_2 production in an electrochemical way, is proven technology. One of the R&D steps is to develop flexible production in an electro-chemical way based on intermittent energy sources and further develop this technology for large scale applications. Prior for companies to start employing this technology, pilots are needed. A follow-up step would be to investigate the way in which these pilots would be eligible for subsidies such as DEI. An alternative option is that government policy facilitates energy storage to become part of the route to realise CO_2-reduction.
- Key research priorities for the PEM electrolysers are reducing the material costs by reduction of the materials used today (membrane thickness and catalyst loading) or replacement with lower cost materials (coatings) and accelerated life testing to determine the performance at variable load. Within the VoltaChem program line PowertoHydrogen ECN develops test protocols and procedures for accelerated stress testing [4].For the battolyser price reductions can be obtained by choosing a 50% smaller MWh capacity and run it at a 100% higher power level. Research is performed at the TUDelft to mitigate the subsequent efficiency loss altogether by gains on other fronts. The second focus for cost reduction should be developing a large scale product of such battolyser and its materials inventory.
- The research on low temperature direct NH_3 synthesis (LT T SSAS) should lead to a device having a stack cost below that of a PEM electrolyser. In addition, it should lead to the removal of the Haber NH_3 synthesis unit and H_2 compressors when H_2 is absent in the product. These should lead to the main cost reduction of the unit overall. Research is needed to bring selectivity, efficiency, current rates and durability forward.
- In this study it is shown that import and/or storage of renewable electricity is required to meet the future CO_2 targets. In Figure 3.3 the required amounts of import and storage for import only and storage only solutions are given. However, this analysis was done with a focus on electricity only. Integration of heat (power to heat), transportation (electric cars, electro-fuels) and industry (power to heat, electrochemistry) in this analysis might give further opportunities for optimization of the energy system. Necessary is then an in-depth study of the entire future electricity system, incorporating other developments such as electrification of heat demand and transport (with the associated efficiency gains), closure of coal and gas generating facilities, and higher carbon prices. It is recommended to launch a study on this.

Appendices

Appendix A: Legislation and safety

NH_3 is an ideal chemical energy carrier, but is also a dangerous substance. In this paragraph, some information about the properties and risks of NH_3 are given. Also the Dutch legislation and regulations are reviewed. Together with the technical options, the design of the logistical supply chains for the business cases of Nuon and Stedin have been discussed.

Properties and risks

NH_3 is gaseous at ambient temperatures and pressure. At -33°C it will be a liquid or when compressed to 6-8 bars at ambient temperature. Vapour pressure is very sensitive to temperature changes. NH_3 is toxic and is lethal at 5000 ppm, but can already be smelled at 5 ppm. This causes people to evacuate themselves in many cases before the critical concentrations are reached.
The flammability of NH_3 is very low, within a very limited window (15-28% in air). Explosive mixtures can generally only be found in confined spaces. Ignition energy is very high.
NH_3 has a strong affinity for water. This can be a risk (body contains mostly water) but also be used in treating incidents (dilution, catching a vapour cloud). Due to the violent reaction, water should never be applied as a fire extinguishing medium for burning liquid NH_3. NH_3 can cause stress corrosion cracking in carbon steel. This can be averted by adding small amounts of water to the NH_3.

Regulations and limitations

NH_3 is a toxic substance. The general opinion is that we want to minimize the production, handling, storage and use of those substances[21]. At first it may appear that there is no opposition to projects involving those substances, but as soon as installations or transportation routes are effectively planned, people will start to have their doubts. Even if the mathematical risk does not increase due to the use of NH_3, the general public's attitude might be negative. If there is significant political objection against NH_3 storage/production/transportation at a certain location, this can decreases plans for a new installation.

When working with NH_3 on a large(r) scale, many (Dutch) regulations and legislations have to be taken into account. It is impossible to explain the effects of all of them. If the location is chosen properly and the correct level of provisioning and a sufficient management system are in place, all of these factors can be dealt with.

Location

A location for production and storage has to be checked against the risk profile of the installation. This means that there has to be a certain distance to vulnerable objects such as housing and infrastructure. The distance depends on many factors, with the scale of the installation being one having the most

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[21] In the study of the Dutch government, the complete product chain of NH_3 (and some other hazardous substances) have been evaluated. https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2010/09/30/ketenstudies-chloor-ammoniak-en-lpg/ketenstudies.pdf

impact. Environmental legislation can also block a certain location. The available room within the legislations is something that has to be checked in detail.

BRZO legislation

NH_3 hold-up in production installations is usually limited. However, the presence of H_2, high pressures and temperatures, create some risks. Production sites will (most likely) be under the "BRZO" legislation. If an installation may contain more than 50 tons of NH_3, it is under BRZO-legislation.

- In the Eemshaven case it is most likely over 200 tons and therefor in the highest BRZO-category. This means additional requirements and more enforcement from the authorities on subjects as compliance, security and firefighting.
- In the Goeree-Overflakkee case, the production facility of NH_3 will probably not exceed the 50 ton of NH_3 threshold as described in the BRZO-legislation. However if a small storage is installed, it is most likely that the installation will be in the 50-200ton range. The additional requirements for such an installation are still there, but not extensive as for the highest category.

Storage

In the guideline PGS-12, http://www.publicatiereeksgevaarlijkestoffen.nl/publicaties/PGS12.html, an overview is given about the correct level of provisioning required for storage and transportation.

Transportation

The government policy is that the production and consumption of NH_3 have to be located near each other as much as possible. There are however only limited restrictions on the transportation of NH_3 in The Netherlands. Some transportation routes have limitations, where NH_3 is listed as a toxic gas (category GT3) in the Dutch "basisnet". When new routes have to be opened up/volumes increase, the risk calculations have to be updated to check if expansion is allowed.
OCI has limits on the amount of NH_3 that can be transported to and from Geleen by RTC. This is an effect of the covenant for the relocation of the fertiliser plants.

NH_3 can be transported by several different modalities; pipeline, seagoing tanker, barge, rail tank car (RTC) or truck. When selecting a certain modality in a project, multiple aspects have to be taken into account, often at both ends of the transport route: e.g. warm, cold or aqueous NH_3, capacity, storage requirements, infrastructure, customer base, transport restrictions, site restrictions, safety/risk profile, transportation costs and investment costs. The various options have been specified for the value chains in the Eemshaven and Goeree-Overflakkee.

Eemshaven Case

Considered options

The P2A system at the Eemshaven site considers electrolysers of 40, 100 and 500 MW_e. The 40 MWe case is based on 2 kton/year excess H_2 available at AkzoNobel in Delfzijl, being used to enable a continuous operation of the NH_3 plant at 25% of its design capacity. The additional 75% is used in periods of excess renewable electricity at low cost. The 100 and 500 MWe cases are considered to explore the impact of using larger electrolysers in either Eemshaven or a remote locations where abundant amount of renewable electricity is available.

Transportation

When building a 40 MW_e production plant, in Delfzijl, the production capacity will be around 20-30 kton/year. Currently AkzoNobel is receiving RTC's from OCI. Storage tanks for NH_3 are not present, only stockpile in 1-2 RTC's. From these RTC's, NH_3 is sent to an installation that produces aqueous NH_3 (25%), of which limited volumes are stored.

- Pipeline transportation is costly: via "buizentrace" around 25 km. Infrastructure does not yet exist. Investment in pipeline are more than 20 MEUR. A local pipeline could be an option to connect the new NH_3 plant to AkzoNobel's Delamine plant.
- Barge transportation is not a likely option. Investments have to be made in new, medium size storage (~1500 t) and pipelines to the docks. Capacity is limited to a mere 15-30 barges/yr.
- Transportation by RTC's or truck are the most likely options. Production will result in 1-1.5 RTC or 3-5 truck transportations a day. A limited storage capacity of at least 3-5 days of production is required. RTC transportation is most preferable from Delfzijl point of view. However in Eemshaven, the tracks need to be extended.
- Limitations in transport of hazardous materials have to be checked for rail and road. For example the rail track to Eemshaven has no NH_3 volumes mentioned in the "basisnet".
- When a 100 MW_e plant (or larger) is built in Delfzijl, a pipeline to Eemshaven is required. Government will probably not allow other transport modalities.
- In Eemshaven, a medium or large storage capacity is required. This will be cold storage, requiring energy for both cooling of the storage and heat for evaporation of the NH_3 before combustion.

Taking into account all of these aspects it was concluded that for the Eemshaven case, storage of cold NH_3 is most likely. If the NH_3 is produced locally a pipeline is the most likely modality. When production is located in Delfzijl, pipeline, truck and RTC are options, mainly depending on the volumes. In case of remote production the seagoing tanker is the only suitable modality.

The conclusion is that a 40 MW_e NH_3 plant in Eemshaven (using 2 kton/year H_2 supplied by AkzoNobel) would require an infrastructure to transport the H_2 from Delfzijl to a. This could be costly. For a larger NH_3 plant in Eemshaven transport of electricity and storage of larger amounts of NH_3 will be limited to Eemshaven-site only .

In the 100 MW_e or 500 MW_e remote renewable energy sources cases, transportation by seagoing tankers, directly from the supplier is the most likely option. Other options could be transportation by barges or by RTC's with a terminal like the one of OCI in Europoort as an intermediate. In both cases large capacity storage is required in Eemshaven.

Legislation

Both Eemshaven and Delfzijl could be sites where NH_3 can be produced and stored. Eemshaven is a location with only a few vulnerable objects (e.g. nearest house at 1.6 km, nearest village at 2 km) around it. However the site is not equipped for large scale use of toxic chemicals.

Delfzijl is equipped for NH_3, most of the provisions are already in place. There are more vulnerable objects around the site. The production of chlorine at the site is an indication that NH_3 could fit in the risk profile.

The presence of vulnerable nature around both sites (Waddenzee) should be studied intensively before applying for permits. NH_3 and waste water emissions from an NH_3 plant are typically very low and are expected to fit within regulations.

Goeree-Overflakkee case

Considered options

The Goeree-Overflakkee site considers electrolysers of 25 and 40 MW_e. The 25 MW_e unit is to be connected to a tidal power plant. The 40 MW_e unit is situated next to a substation. The 25 MW_e unit should all renewable electricity directly while the 40 MW_e aims to improve network flexibility.

Transportation

- There are only two modalities available on the island (transportation by truck or barge). The other options would require huge investments.
- Transportation by barge is not a real option since it would require a large storage of ambient temperature NH_3. This will have a large impact on the permit. Also an investment in a pipeline to a harbour is required. Harbours on Goeree-Overflakkee are (most likely) not industrial harbours and will probably need additional facilities and permits.
- Since the market for transportation of NH_3 in trucks is limited in the Netherlands, the product should be shipped to the Europoort terminal of OCI. The distance is about 30-60 km depending on the exact location of the production unit and the preferred route. From the terminal it can be transferred to other modalities or cooled and stored in the large tanks. Yearly volumes of 50-100 kt can be passed through that terminal without much interference. Larger volumes need more study.

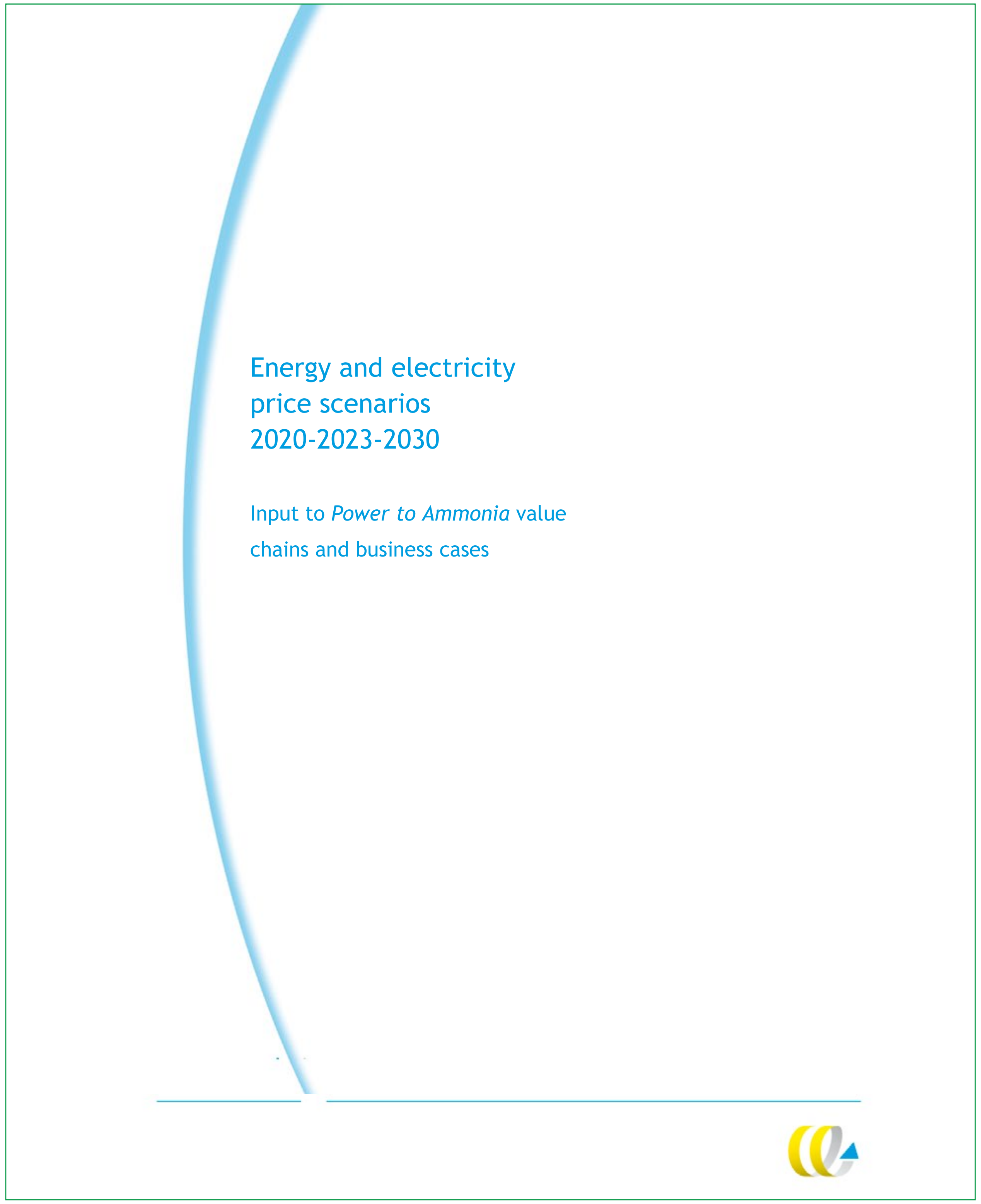
In the Goeree-Overflakkee case transport by truck to a NH_3 terminal (e.g. OCI terminal Europoort) is the only option, mainly due to the lack of infrastructure for the other modalities. Both ambient temperature NH_3 and aqueous NH_3 can be selected as products. Aqueous NH_3 has the lowest risk profile, but has limitations for the volumes that can be sold. When an economic process can be found to process NH_3 into fertilisers the need for NH_3 transportation is obviously omitted.

Legislation

The island of Goeree-Overflakkee is not familiar to any (chemical) industry. It requires certain efforts to create all the correct provisions. Although the island is not densely populated, tourism and nature will provide significant hurdles for choosing a NH_3 production site. The small size of the installation and limited storage capacity can be advantageous. Remotely operated installations and truck transportation are disadvantageous. Performing a quantitative risk analysis (QRA), can answer some of these questions but is beyond the scope of this study.

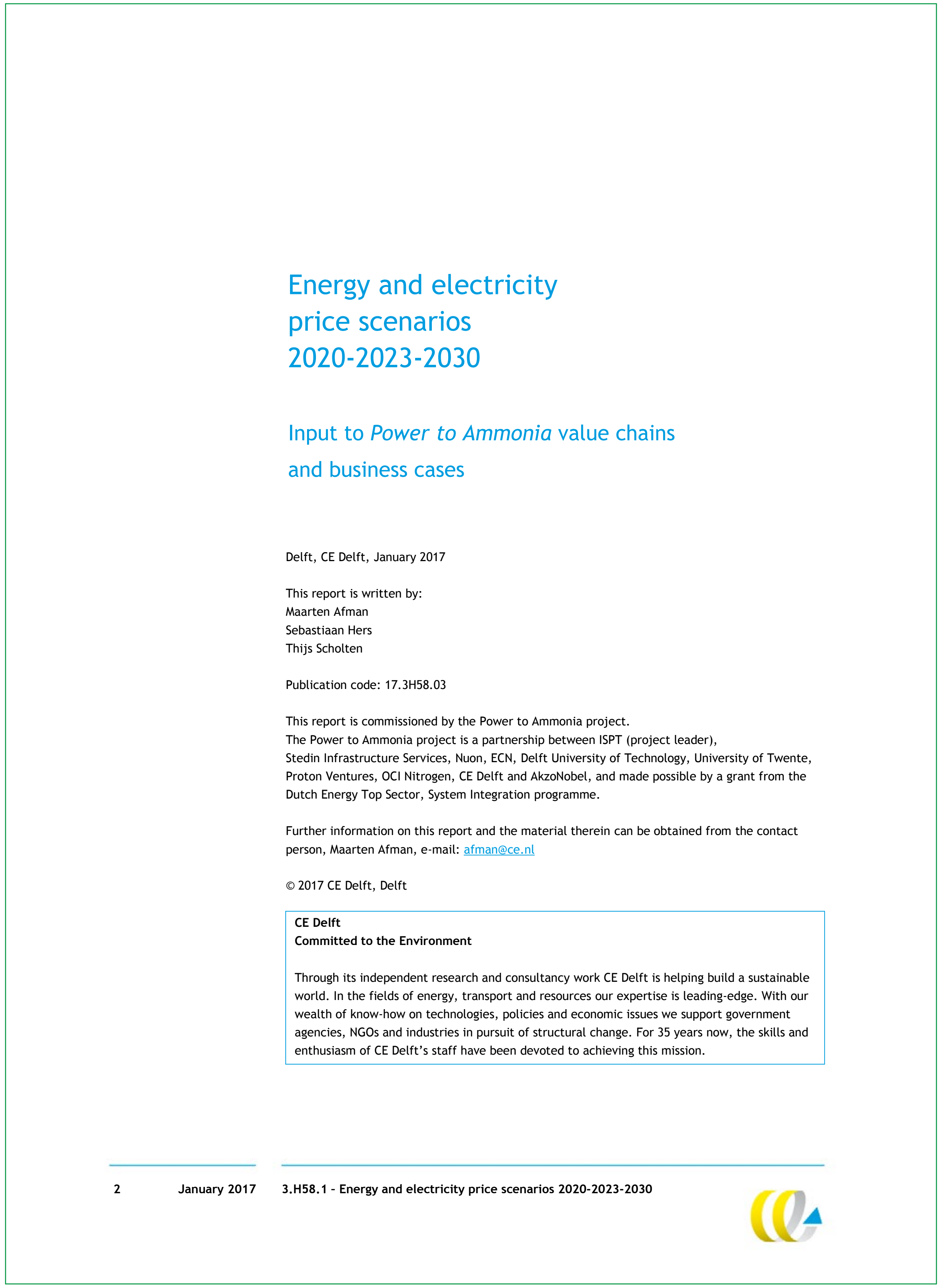
Most of the dunes on Goeree-Overflakkee as well as the Grevelingen and Krammer-Volkerak lakes are considered Natura2000 areas. A significant reduction of nitrogen deposition is required in those areas. It will be difficult to fit in an (small scale) NH_3 plant in that area, especially with a lot of product handling during loading due to increased risk of nitrogeneous emissions. This will be a relevant factor for building a NH_3 unit near the tidal facility at the Brouwersdam. For the inland locations (e.g. Middelharnis) less problems are expected with regards to environmental issues.

Appendix B: Energy and electricity price scenarios



Energy and electricity price scenarios 2020-2023-2030

Input to *Power to Ammonia* value chains and business cases



Energy and electricity price scenarios 2020-2023-2030

Input to *Power to Ammonia* value chains and business cases

Delft, CE Delft, January 2017

This report is written by:
Maarten Afman
Sebastiaan Hers
Thijs Scholten

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Further information on this report and the material therein can be obtained from the contact person, Maarten Afman, e-mail: afman@ce.nl

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Through its independent research and consultancy work CE Delft is helping build a sustainable world. In the fields of energy, transport and resources our expertise is leading-edge. With our wealth of know-how on technologies, policies and economic issues we support government agencies, NGOs and industries in pursuit of structural change. For 35 years now, the skills and enthusiasm of CE Delft's staff have been devoted to achieving this mission.

Contents

1 Introduction

The more we proceed with the energy transition towards renewable and sustainable energy, the greater the need to innovate on a system level: we have to find and implement options that make the energy system more flexible. This must be done in a way that fits variable renewable energy sources - ample supply at some time, and shortages at other times. Technologies like Power to Ammonia, that convert electrical energy to a chemical form, store the energy for a length of time, allowing for conversion back to electricity if necessary, are just the options that are important to investigate.

As an important part of the mission of CE Delft is to contribute to structural change towards a sustainable energy system, we gladly participated in the joint Power to Ammonia project of 2016 and contributed to the development of this option.

In the project, our main contribution was two-fold:

1. Knowledge transfer within the consortium on the electricity market. For this we organised two workshops with the goal of raising the knowledge on the electricity market, the current institutional arrangements in the electricity markets, and what will change given projected developments.
2. Develop energy and price scenarios for the time scale to be used in the P2A value chains (2020-2023-2030). The scenarios were developed based on input from the consortium partners and tailored to the sensitivities surrounding the Power to Ammonia value chain. Electricity prices were simulated with the PowerFlex market simulation model.

This report describes both contributions, with emphasis on the energy and price scenarios.

2 Electricity market

Because the Power to Ammonia project brings together a number of topics and sectors, a shared knowledge level is needed on the energy system, and future challenges thereof. Two workshops were held for this purpose.

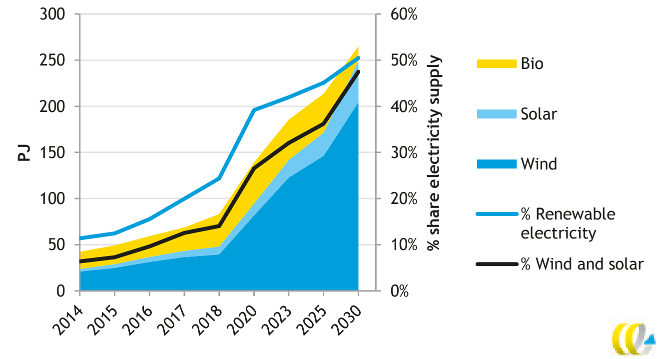
Workshop 1: electricity market
For electrochemical conversions, the electricity system is of obvious importance. Electricity is an energy carrier of a special nature. Because it cannot be stored without any form of conversion, maintaining the momentary balance between consumption and supply of electricity is a challenge that is reflected in a rather complex market design.
The main topics covered were:

1. Wholesale market: OTC long term, bilateral, day ahead spot, intraday.
2. Balancing mechanism and markets.
3. Transport market.
4. Price formation in the Energy Only Market model, regulation.
5. Flexibility requirements and flexibility provision.

Workshop 2: transitions in the energy system and scenarios
The second work shop recapped the main results of the first workshop and continued with wider trends in the Dutch (see figure) and European energy systems and the decarbonisation challenge. Given these perspectives, the outlines and scenario design were discussed for the electricity market scenarios to be developed. Due to the large volumes of electricity required for producing ammonia via electro-synthesis in large quantities, spot market pricing is the relevant market to assess. The next chapter of the report fully details the scenarios developed.

Figure 1 Development of the supply of renewable electricity in the Netherlands

As an illustration, the figure shows the expected development in renewable electricity in the Netherlands. In 2030, wind and solar will contribute to 250 PJ towards the Dutch energy supply, a share of about 50% in the electricity demand and 13% of total (current) energy demand.



3 Energy and electricity price scenarios

3.1 Energy scenarios for Power to Ammonia

For Power to Ammonia business cases, future electricity prices and its dynamics on different timescales are important ingredients. Price scenarios are input to:

1. Selecting a suitable operation of the P2A plant: the operational dynamics, when to operate, when not, starts, stops, etc.
2. A suitable dimensioning of the P2A plant as well as of buffer tanks, etc.
3. Ultimately the expected profitability of the 'value cases', either direct from the volatility in prices simulated, or through the arbitrage between power and ammonia markets, and so on.

Therefore, one of the CE Delft work packages in the Power to Ammonia project was to develop a number of suitable energy price scenarios to be used in the three business cases. This chapter details the scenarios, the modelling approach with the PowerFlex energy market simulation model and the results.

3.2 Scenario selection

The first goal of scenarios is to do baseline projections for the future.
The second goal is to be able to investigate the key sensitivities in the P2A business cases that are caused by power prices. This combined goal means two things for the scenario design. First of all, price scenarios should mimic a plausible future path given our best knowledge at this point; secondly scenarios should capture some of the profound uncertainties that relate to the business case. Therefore the scenario design should capture the relevant uncertainties.
If we look at uncertainties surrounding power prices in the time frame 2017-2030, a number of important aspects are uncertain to a larger or lesser extent. These uncertainties relate to:

- fuel prices, especially coal and gas;
- CO_2 prices;
- generating technologies and installed capacities;
- renewable energy, installed capacity;
- demand; dynamics thereof (how it fluctuates over time); elasticity of demand and demand response;
- regulatory, i.e. market design, capacity payments, RES remuneration scheme affecting power market bidding behaviour, etc.;
- technology: adoption and learning rates of innovative demand and supply technologies (such as EV, solar PV, heat pumps, P2H, P2G, etc.).

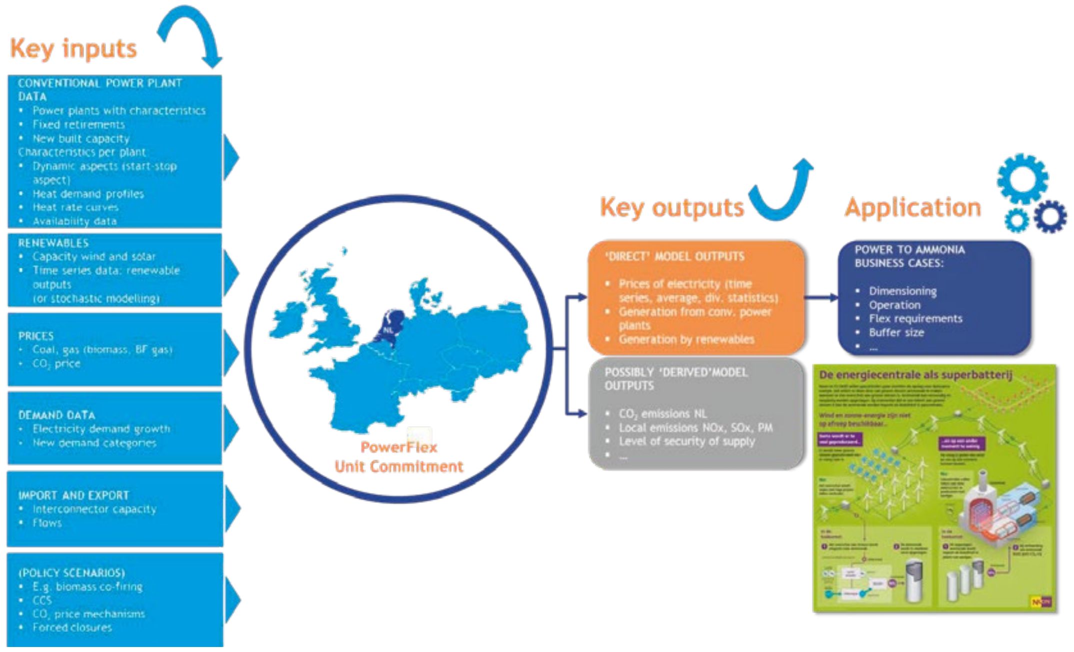
Then, the further we go in the future, there are some fundamental unknowns, the 'unknown unknowns': new demand categories of technologies, not yet existent that influence the power price; sudden events and catastrophes.

Working with scenarios aims to capture a number of these uncertainties. With a good scenario design, one is able to elucidate the key sensitivities in the business cases with a limited number of scenarios or years to simulate. With a smart scenario design, one is able to deal with the uncertainties without making the analysis itself overly complex.

3.3 The PowerFlex model

First of all, it is good to know what parameters are important for the power price simulation by describing what is needed to do a simulation with a fundamental market simulation model like PowerFlex. The key input data of impact to power price formation as calculated by the PowerFlex unit commitment and dynamic dispatch model is illustrated in Figure 2. Some more information on the model is in the Box 1. The model is further described in CE Delft (2016).

Figure 2 Inputs and outputs to the PowerFlex model



Box 1 PowerFlex - commitment model with dynamic dispatch

The PowerFlex unit commitment model is focussed on accurately simulating dispatch decisions of power generating assets on the individual unit level and from this obtain very realistic estimates of spot market bidding behaviour and thus spot market price formation. The PowerFlex model captures the full dynamics of the operation of the power generation sector and is rich in the sense that peculiar characteristics of the Dutch system are accurately represented. One unique characteristic is the Dutch market's large CHP fleet. The model includes dynamic economic dispatch, quadratic heat rate curves, must run, CHP, heat demand, minimum up/down times and start costs, and for balancing/short term dispatch: ramping capabilities. The model is mathematically unique in that it contains an advanced solver that is able to converge on price formation in relatively few computations steps saving several orders of magnitude computational time compared to models that rely on numerical solving of the full computing space. Due to this short computational time and the ability to model short term markets, the model aims to be one of the more advanced electricity market dispatch models.

3.4 Scenario design

A good approach is to start from one already established/developed scenario and take that as a baseline if we deem it sufficiently plausible. Then we decide what years to further detail the scenarios for, and then we focus on the parameters to vary and the way this is done, reflecting on the profound uncertainties that are highly relevant for the business cases we want to assess.

Baseline

One recent and well-established scenario for 2030 is the one published by ECN & PBL in the National Energy Outlook (NEO), 2015 version (ECN; PBL; CBS; RVO.nl, 2015). The NEO contains two pathways to 2030:

- *Fixed policy (F)*: this pathway incorporates the currently (as of 2015) 'fixed' policies (baseline).
- *Fixed and intended policy (F&I)*: this pathway incorporates the same policies as the other one, but now also the 'intended' policies on a national and EU level. This pathway achieves a higher share of decarbonisation in 2030.

We will use the NEO F&I as the most likely baseline trajectory for the scenarios to simulate, the other one being overly conservative. This baseline scenario will then yield the primary data for the time horizon under study - 2020, 2023 and 2030 - such as demand projections, installed capacities of wind, solar, etc.

Time horizon

The scenarios should capture a for Power to Ammonia relevant time span. For the P2A project three years were selected (2020, 2023, 2030) according to the envisioned phase of deployment of different Power to Ammonia technology options and value cases[1].

Level of renewable energy supply

This is a key aspect of Power to Ammonia applications. The NEO expects a development of installed capacities for wind and solar in the Netherlands, going from 7 GW wind and 6 GW solar PV in 2020 to 11 GW wind and 17 GW solar PV in 2030.

For the year 2030, we will compute an additional scenario with a more progressive vision on the renewable energy supply capacities, with a larger share of, primarily, offshore wind generation. Whilst the NEO F&I sees continued growth of solar PV between 2023 and 2030, a very modest growth of onshore wind, offshore wind is actually declining from 2023 due some oldest wind parks being at end of life. Therefore, we decided to simulate an additional **2030 'high-RES' scenario** with more progressive renewable energy supply capacities: 20 GW wind offshore, 8 GW wind onshore, 20 GW solar PV. For Germany, we use the prognosis from (Netzentwicklungsplan, 2016) for all years.

Coal, gas and CO_2 prices

Supposedly, for business cases where an electric ammonia production plant cycles on a daily basis (as driven by power prices), the price volatility on a daily/weekly basis is the main value driver. As electricity prices in peak and off peak are typically set by gas- and coal-fired facilities respectively, the diurnal electricity price cycle is heavily driven by the underlying fuel and emission costs. Hence, the spread between coal- and gas prices, price of CO_2 emission allowances and the installed capacities coal/gas are important

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[1] The Goeree-Overflackee case plans to be operational around 2020 and the Eemshaven/Delfzijl case envisions to be operational around 2025/2030.

drivers for the diurnal cycle. In addition, the level of RES supply is an important daily and weekly volatility driver, since RES supply can show high volatility in these timeframes.
As these prices are a very direct impact factor for the power prices in most if not all of the hours of the year, we will include two alternative sets of coal, gas and CO_2 prices in the scenarios: high and low prices.

Coal and gas prices from the ECN NEO are substantially higher than current projections by specialised pricing data providers such as IHS, ICIS/Platts, and others. Therefore it is relevant to investigate the impact of coal and gas prices.

A note on consistency between fuel and CO_2 prices is useful for clarification. Over a longer timeframe (equilibrium), low prices for coal and gas could be viewed to be consistent with an ambitious and world-wide effective climate policy, as a result of limited demand for fossil energy sources (see e.g. (PBL and CPB, 2015)). On the other hand, high prices could be viewed to be consistent with a not so effective climate policy and hence arguably lower CO_2 prices. We will not use this aspect in the scenario design, we will use a combination of high CO_2 prices with high fuel prices, to show the maximum sensitivities for these prices.

Also a note on ammonia prices is relevant. Ammonia prices depend largely on gas and more limitedly on coal prices. In the business cases it is essential that ammonia prices are used that are consistent with the coal, gas and CO_2 prices used for the power market simulations.

Flexibility provision

The PowerFlex model is able to simulate demand side flexibility in a number of ways (e.g. power to heat boilers for heat coupled power plants).
It would be interesting to have a look at what would happen in the 'cheap hours', i.e. the 100-1,000 hours where a number of technologies compete with electric ammonia synthesis. However, it was chosen not to simulate this type of competing demand response, in order to show the 'raw effects' the scenarios have on the volatility of the power market.
The 'flexibility' in the simulation model is therefore largely on the supply side: thermal power plants of varying flexibility capabilities. An additional source of flexibility is German pumped hydro storage. This is modelled for its current capacity and known capacity expansion plans.

RES curtailment

RES curtailment is also a flexibility source, but in the model setup it is not incorporated. If RES infeed in the scenarios is too high for the model's solver to match (i.e. demand cannot be increased anymore), it will show as a price that drops below zero. Depending on the amount of oversupply, the model will show *highly negative* prices. These highly negative price excursions result from a modelling artefact and do not represent realistic pricing behaviour, so in post-processing these negative prices were put at zero.

3.5 Scenario details

Simulations were executed for three future years, with for the year 2030 two variants (NER and high-RES). Furthermore, all scenario-years were simulated under two sets of fuel/carbon price paths. Demand was taken from the NER for the Netherlands and from (Netzentwicklungsplan, 2016) for Germany.

Details on capacities used are in Table 1, on the low fuel and CO_2 prices in Table 2 and higher prices in Table 3.

Table 1 **Capacities in the simulated scenarios**

			2020	2023	2030-NER	2030-high-RES	2020	2023	2030
			The Netherlands				Germany		
RES cap	Wind on land	GW	5.1	6.1	6.7	8.0	51.3	58.8	76.3
	Wind off-shore	GW	2.3	4.5	4.3	12.0	6.3	8.8	14.5
	Solar PV	GW	5.9	9.4	17.3	20.0	47.2	51.8	57.4
Conventional generation	Nuclear	GW	0.5	0.5	-		8.1	0.0	0.0
	Lignite	GW	-	-	-		16.7	15.8	10.3
	Coal	GW	3.4	3.4	3.4		24.9	23.5	16.4
	Gas	GW	18.5	18.5	18.5		31.2	35.0	39.7
	Oil		-	-	-		2.0	1.9	0.8
	Biomass	GW	0.0	0.1	0.1		6.9	6.9	6.9
	Blast furnace gas	GW	0.6	0.6	0.6		1.9	1.9	1.1
	Waste	GW	0.6	0.6	0.5		1.8	1.8	1.8
	Total conventional	GW	24.0	24.0	23.5		93.6	86.8	77.2
Flex	Pumped storage	GW	-	-	-		6.7	8.9	12.8
	Batteries	GW	-	-	-				
	Power to heat	GW	-	-	-				

For all scenario-years we have plant capacity and technical capabilities from our proprietary data set. This includes the expected plant closures and new built capacity. In addition, we have modelled premature closure of the two coal fired power plants from the 1990's: Hemweg unit 8 in Amsterdam as well as Amercentrale unit 9 in Geertruidenberg. We modelled this capacity to be offline in all scenario-years (so also 2020). With regards to new investments, we have modelled only new capacity going online as a replacement for units that are closed, but not more than that. The model doesn't automatically add capacity if prices from the simulation would be too high (though this could be done manually).

Table 2 **Lower prices scenarios (€$_{2015}$)**

			2020	2023	2030
Fuel and carbon prices	Coal price	€/ton ARA	44.9	55.0	55.1
	Gas price	€/MWh HHV	13.4	20.2	20.8
	CO_2 price	€/ton	11.1	13.1	20.1

In the 'lower prices' scenario, the source of coal and gas prices is an established commercial provider of forecast data for these commodities, estimates dated March 2016, and for CO_2 the prices of the ECN NEO are used.

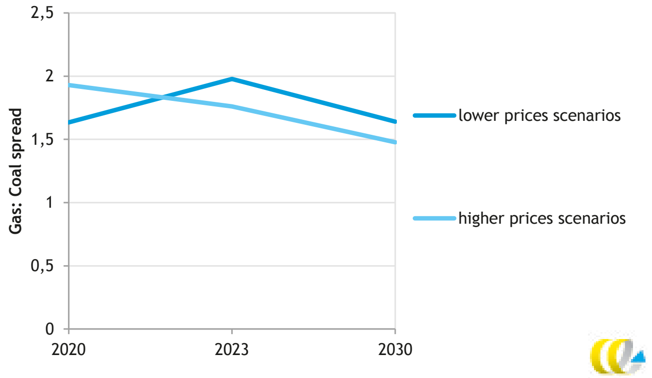
Table 3 Higher prices scenarios (€$_{2015}$)

			2020	2023	2030
Fuel and carbon prices	Coal price	€/ton ARA	81.5	83.5	88.5
	Gas price	€/MWh HHV	28.8	30.9	34.0
	CO_2 price	€/ton	19.1	25.6	40.6

In the 'higher prices' scenario, the prices for coal, gas are all from ECN NEO. For CO_2 prices we have used the WLO-scenario 'High' (published December, 2015) (PBL and CPB, 2015).

The following picture in Figure 3 shows the development of the Gas: Coal spread including the cost of CO_2 in the high and lower price scenarios.

Figure 3 Gas: Coal spread



Imports/exports

For import/export the model has two ways of running it: a single country version and a multi-country version.
In the first case the model works with scaled historic imports. This is useful to study effects in the Dutch system in the absence of what we would call 'regime changes'. This would entail an assumption that e.g. RES infeed in the Netherlands would be much correlated with neighbouring countries, requiring balancing within the Netherlands, which is a simplification.
In the multi-country option the model also incorporates surrounding countries and this enables capturing relevant dynamics in these markets as well, for example the German nuclear phase-out. During the workshop session we had discussions on Belgian developments, but there is no clarity on closure dates, so it was decided not to model this market.
For the model results presented in this report, the multi-country version was used, in which the Dutch and the German market were modelled.

3.6 Results

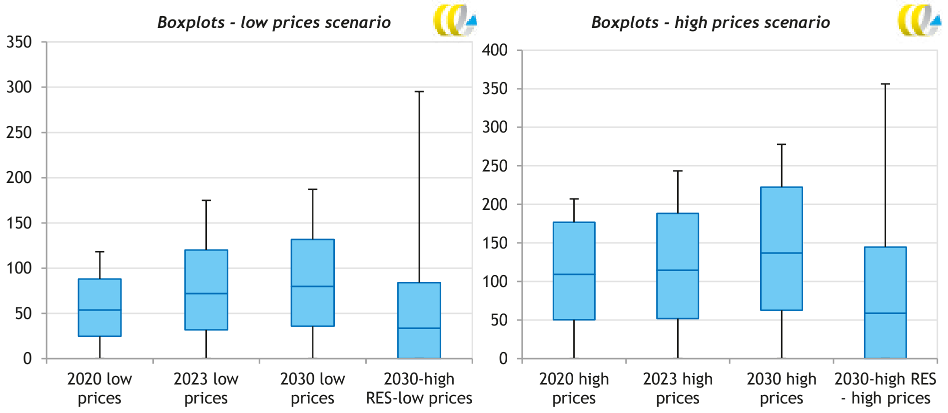
The modelling results in time series of hourly electricity prices and the precise dispatch of the different generating units, large sets of data. This section details the price scenarios, depicted in a number of figures.

3.6.1 Statistics - boxplots, frequency distribution

Looking at Figure 4, we can observe that prices are expected to increase modestly from 2020 to 2030 scenario years. This is arguably driven by rising fuel and CO_2 prices. The 2030 high-RES scenario is the exception; in this scenario the majority of prices tend to be lower but there are also some higher prices or price extremes.
Furthermore, the boxes become wider over time, indicating that volatility in prices is increasing (50% of the simulated prices fall in the box). This is also seen in the widening whiskers, especially in the high-RES scenario.

Observing the frequency distribution plots of Figure 5, we note that the histograms get wider with more VRES and through time – also clearly indicating that volatility tend to increases, the 'bell shape' widens (flattens).
The 2030 high-RES scenario stands out with lower prices and much stronger price extremes.
In the histograms a spike in the 0-10 €/MWh category is visible. This spike is an artefact of post-processing, where al negative values have been set to zero (see Section 3.4 for more on this).

Figure 4 Boxplots of simulation results: median, first and third quartiles and extreme values



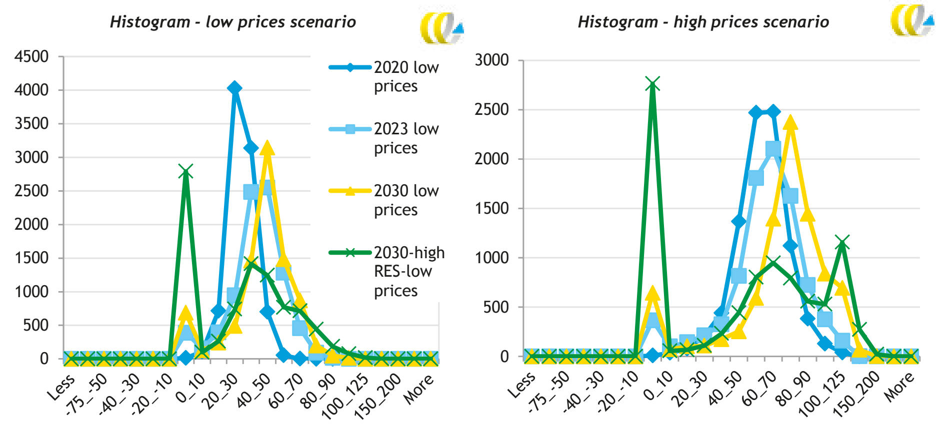


Figure 5 Frequency distribution of simulation results - counts of hourly values

Histogram - low prices scenario

Histogram - high prices scenario

3.6.2 Statistics - average prices

Figure 6 shows the year-average price of electricity, where only the 10, 20, 30, 40 or 50% cheapest hours of the year have been included in the average. Two things stand out. First of all, especially the 10-20% cheapest hours (900-1,800 hours of the year) show a declining trend over time. We expect that progression in renewables infeed is the primary reason for this.
The second thing that stands out is that the 'high-RES' scenario (28 GW wind and 20 GW solar) is really low during even 50% of the hours of the year - this reflects that in this scenario, the demand is way too little to accommodate excesses of RES.

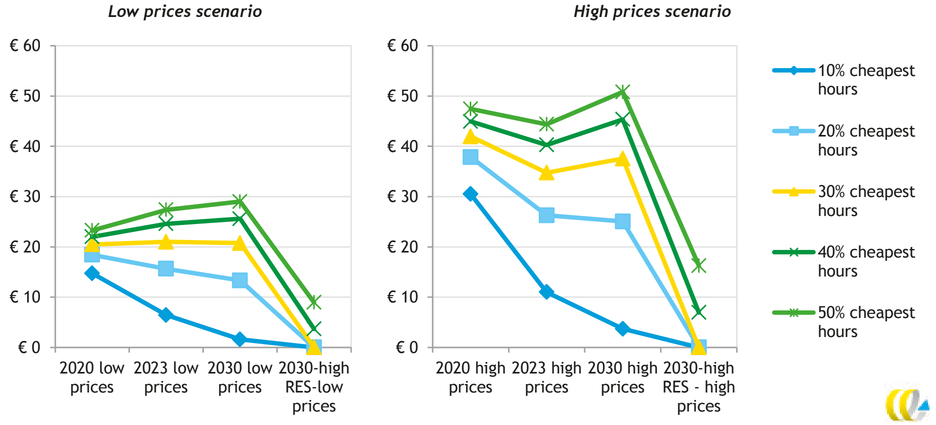


Figure 6 Average price during the X% cheapest hours of the year

Low prices scenario

High prices scenario

Figure 7 is similar to Figure 6, but instead of low prices, this figure reflects the most expensive hours of the year. In this figure, we see all lines rising as time progresses, so the prices rise, essentially driven by scenario fuel and CO_2 prices.

One thing is interesting to note, and that is that the prices in the 2030 'high-RES' scenario are higher than the prices in the 2030 regular scenario. This cannot be due to fuel or CO_2 prices, which are unchanged compared to the regular 2030 scenario. Therefore, we conclude that this is purely driven by *flexibility constraints* of the generating park, requiring the use of more expensive generating units. This leads to more price volatility. An insight such as this can only be generated from market simulation with a market model that captures flexibility constraints of thermal units.

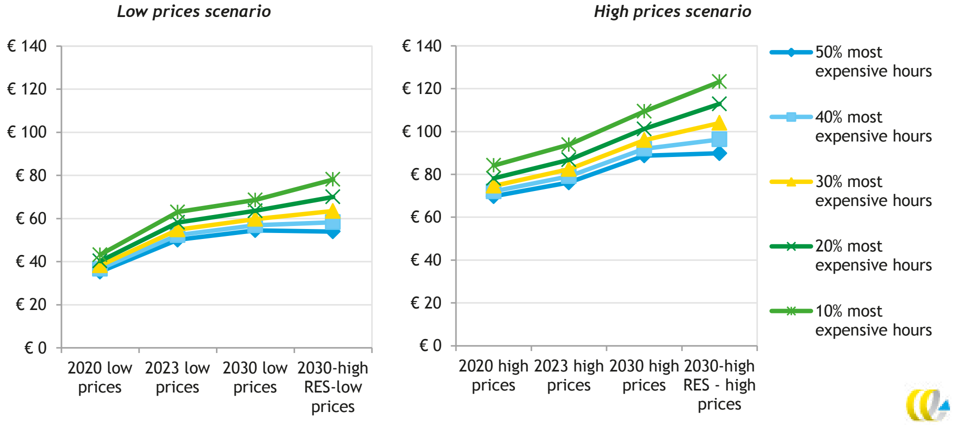


Figure 7 Average price during the X% most expensive hours of the year

Low prices scenario

High prices scenario

Some more statistics for the simulation results are included in Table 4.

Table 4 Simulation results for the scenarios

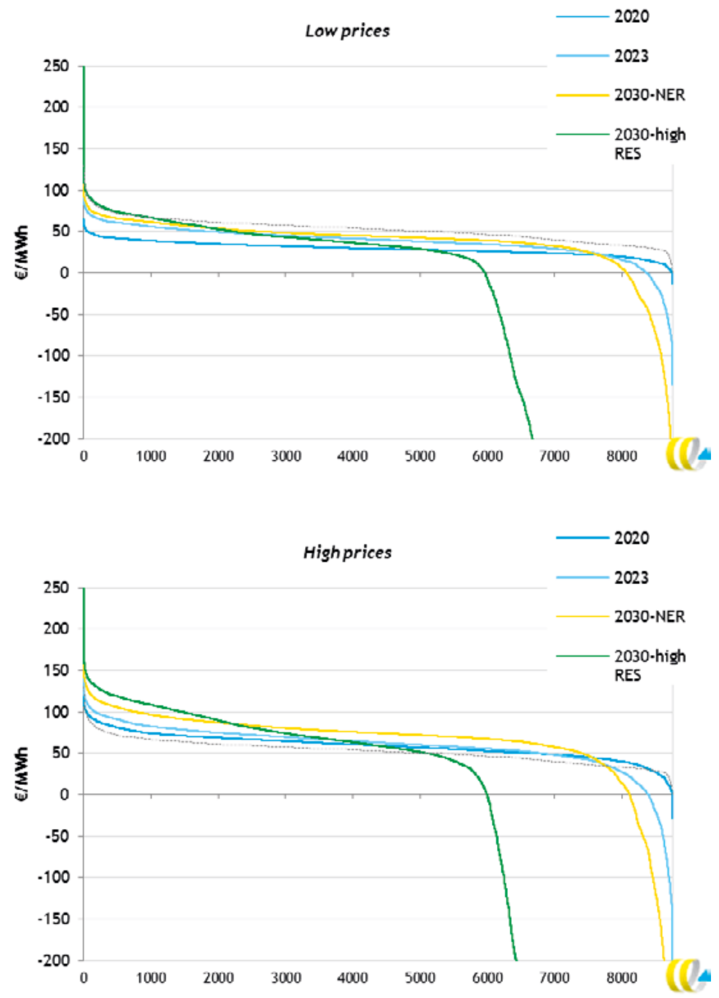
		Low prices scenario				High prices scenario			
		2020 low prices	2023 low prices	2030 low prices	2030 high RES- low prices	2020 high prices	2023 high prices	2030 high prices	2030 high RES - high prices
Avg. price	€/MWh	29.3	38.8	41.8	31.4	58.6	60.3	69.8	53.0
Std. dev	€/MWh	7.9	15.3	17.9	26.7	14.8	22.1	27.8	43.2
Maximum	€/MWh	64.3	103.0	107.4	261.7	123.1	150.4	167.4	396.3
Q1	€/MWh	24.6	31.8	35.8	0.0	50.2	52.0	62.9	0.0
Median	€/MWh	29.1	40.0	44.0	33.6	59.1	62.7	74.3	58.8
Q3	€/MWh	34.2	48.2	52.1	50.3	67.7	73.7	85.4	86.0
Minimum	€/MWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
N° of hours with price below	<0	0	0	0	0	0	0	0	0
	<1	18	402	696	2,799	9	374	649	2,768
	<5	57	465	747	2,834	20	415	680	2,787
	<10	124	546	814	2,891	45	467	715	2,819
	<20	840	941	1,055	3,155	124	611	816	2,887
N° of hours with price of at least	>0	8,746	8,372	8,074	5,968	8,751	8,394	8,117	5,997
	>50	57	1,841	2,609	2,206	6,619	6,795	7,407	5,086
	>60	3	558	1,128	1,439	4,151	4,989	6,815	4,284
	>70	0	103	259	724	1,672	2,886	5,420	3,336
	>80	0	14	62	284	551	1,260	3,045	2,543
	>100	0	1	1	22	39	162	764	1,455
	>120	0	0	0	4	1	10	120	437

3.6.3 Price duration curves

Price duration curves show the prices of the year sorted by price from high to low. This allows for comparison of the extremes can be compared efficiently. For reference, the 2013 Dutch day ahead market results (APX DAM) are included as well.

Warning: The graphs show raw simulation results without the post-processing of the negative hours (where the model cannot solve due to RES-oversupply). In the most extreme scenarios (especially 2030 high-RES) this leads to exceedingly large negative prices. These negative values should in no case be used for quantifying a business case; RES curtailment would be a flexibility option that would take place there.

Figure 8 Price duration curves for low and high prices



4 Conclusion

For Power to Ammonia value cases, future electricity prices and its dynamics on different timescales are important ingredients.

Simulations of the power market were conducted and have resulted in a set of time series of simulated power prices for the day ahead spot market.
The time series show that:

- The average (baseload) electricity price level depends strongly on prices for coal, gas and CO_2.
- Increases in renewable electricity depresses prices, but this effect is most pronounced during the 900-1,800 hours that the price is already relatively low (the tail of the price duration curve).
- Over time, the volatility of the electricity price is expected to increase significantly. This is most extreme in the high-RES scenario for 2030.

The high-RES scenario for 2030 shows that in this scenario, with 28 GW wind and 20 GW solar PV, there is a clear need for demand response that can absorb oversupply of wind and solar. We also see that the high share of renewable infeed makes balancing the system more expensive during the hours with lower RES infeed, leading to higher prices. This will ask for flexible power production, preferably from renewable or CO_2 neutral fuels, to accommodate the times without much wind and solar.

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Appendix C: Dutch regulations

When working with ammonia on a large(r) scale, many (Dutch) regulations and legislations have to be taken into account. This is a non-limitative list (most in Dutch) with the most important in bold.

- Zorgplicht
- Wabo en BOR (omgevingsrecht)
- Activiteitenbesluit/regeling
- Besluit MER
- EPRTR (E-MJV)
- IPPC: Bref WWWG & Storage
- PGS12: NH_3 storage and transport
- Bevi/Revi (QRA)
- Wet Geluidhinder/trillingen
- Bodem: NRB en besluit bodemkwaliteit
- Wet luchtkwaliteit
- Afval: toetsing LAP
- Bibob
- Water: RWS of Waterschap
- Natuurbeschermingswet/PAS
- CO_2 emission trade (ETS)
- Bestemmingsplan
- Bouwbesluit
- Welstandstoetsing
- Grondonderzoek (archeology & explosives)
- Seveso/BRZO - MRA/BNO
- Risicoregister
- Arbozorg
- Inspections (integrity)
- ADR/transport (road, rail, water, sea)
- Basisnet
- NEN normen

Appendix D: Assumptions business cases Eemshaven

Assumptions Red business cases

General assumptions

Discount rate	7%
Valuation horizon	20 years
Tax rate	25%
Inflation	0%
Base year (NPV)	2024
Commercial Operations Date (COD)	2027

Business Case Red 2 (Remote NH_3 production from PV-generated electricity)

Lifetime	20 years
Load factor PV	0.19
Electricity price	15 EUR/MWh
Electrolyzer capacity	500 MW(e)
Availability (E to NH_3)	92%
Efficiency (E to NH_3)	8.6 kWh(e)/kg
Total CAPEX	586 MEUR
Maintenance OPEX	2% of CAPEX/yr
Staff costs	0.75 MEUR/yr
Transport to Eemshaven	30 EUR/ton

Business Case Red 3 (Remote NH_3 production from a baseload renewable source)

Lifetime	20 years (incl. replacement investment in year 10: 60% of initial CAPEX)
Load factor Geothermal	1.00
Electricity price	25 EUR/MWh
Electrolyzer capacity	500 MW(e)
Availability (E to NH_3)	92%
Efficiency (E to NH_3)	8.6 kWh(e)/kg
Total CAPEX	641 MEUR
Maintenance OPEX	2% of CAPEX/yr
Staff costs	0.75 MEUR/yr
Transport to Eemshaven	30 EUR/ton

Assumptions Blue business cases

General assumptions

Discount rate	7%
Valuation horizon	15 years
Tax rate	25%
Inflation	0%
Base year (NPV) Co-firing NH_3 100% NH_3	 1-1-2018 (FID) 1-1-2023 (FID)
Commercial Operations Date Co-firing NH_3 100% NH_3	 1-1-2021 1-1-2026
Reference case	Dispatch on 100% CH4
Market price curves	CE Delft curves
SDE+ duration	15 years
Co-firing %	10% (LHV)
NH_3 price	300 EUR/ton (fixed)/ CH4 indexed
Max Load (NH_3)	476 MWe
Net efficiency @ full load (NH_3)	53.1%
CAPEX (real 2016) Co-firing NH_3 100% NH_3	 50 MEUR 246 MEUR
OPEX	3% of CAPEX/yr

Groen van Prinstererlaan 37
3818 JN Amersfoort
the Netherlands
+31 (0)33 700 97 97
info@ispt.eu
www.ispt.eu