Power-to-Ammonia: Rethinking the role of ammonia – from a value product to a flexible energy carrier (FlexNH$_3$)

Project Systeemintegratie Studie

Final Report

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Summary

This report focuses on the feasibility of the power-to-ammonia concept. Power-to-ammonia uses produced excess renewable electricity to electrolyze water, and then to react the obtained hydrogen with nitrogen, which is obtained through air separation, to produce ammonia. This process may be used as a “balancing load” to consume excess electricity on the grid and maintain grid stability. The product, ammonia, plays the role of a chemical storage option for excess renewable energy. This excess energy in the form of ammonia can be stored for long periods of time using mature technologies and an existing global infrastructure, and can further be used either as a fuel or a chemical commodity. Ammonia has a higher energy density than hydrogen; it is easier to store and transport than hydrogen, and it is much easier to liquefy than methane, and offers an energy chain with low carbon emissions.

The objective of this study is to analyze technical, institutional and economic aspects of power-to-ammonia and the usage of ammonia as a flexible energy carrier.

Various scenarios for different locations were modeled at different scales of capacity. Historical KNMI (Koninklijk Nederlands Meteorologisch Instituut) data were used to estimate wind and solar energy production for various locations for each hour of the year. The pattern of the renewable electricity production was found to be location specific, but for a given location the correlation between the surplus electricity consumption and the electrolyzer capacity showed similar tendencies, independent of the technical boundaries of the scenarios.

Both smaller (local-scale) and larger (national-scale) power-to-ammonia scenarios were investigated. The ammonia synthesis step is a high pressure and temperature catalytic process and requires a continuous reagent flow. The intermittent nature of the renewable electricity sources does not allow a steady flow of hydrogen. Two main strategies were identified for the local scenarios to secure the continuity of the renewable ammonia synthesis step: i) the adaption of a hydrogen storage tank that acts as a buffer and ii) electricity import from the grid during

periods of no renewable electricity generation for maintaining the ammonia production at a minimum rate. For larger national-scale scenario only the storage-buffer of hydrogen was used, in order to focus on the grid balancing aspect of the power-to-ammonia process.

The output of these scenarios resulted in the finding that the main steps of the power-to-ammonia process (hydrogen production through water electrolysis, nitrogen separation from air and ammonia synthesis) are technically feasible using proven technologies powered by renewable electricity sources.

Ammonia is a flexible chemical that can be used as a chemical commodity and as an energy carrier. Given this flexibility of usage, and given the fact that the supporting technology and infrastructure for the transport, distribution and usage of ammonia is already in place, ammonia is a good candidate to be a large-scale, low-carbon, energy carrier of the future. Power-to-ammonia can provide the flexibility required in the future with an increased share of intermittent renewable energy and represents a direct link between the energy and chemistry sectors. The concept could facilitate the energy transition for the Netherlands to meet its greenhouse gases emissions targets for 2020.

Furthermore, capital costs, operating parameters and other financial assumptions of a power-to-ammonia plant were used in an economic model to calculate the break-even point at which the total cost and the total revenue are equal. The renewable energy production profile determines the size and the rate of the ammonia synthesis plant. The results showed that a power-to-ammonia plant at local scale with a nominal electricity consumption of around 1.5 MW or smaller was technically feasible but not from a financial point of view. However, when the scale of the renewable electricity production and the power-to-ammonia plant is increased to 15 MW, a successful business case is feasible. The transport and storage costs of ammonia in general are significantly lower than that for hydrogen. The storage cost of hydrogen is significant higher when it is stored for a longer period.

The elimination of the costly hydrogen storage tank from the plant design for the local scenario where electricity is purchased to run the process continuously at the lowest possible production rate offers an economical advantage. In this local scenario the results suggest that at windier locations it is economically more advantageous to only sell the produced electricity, losing any excess energy produced. In this case, as the power available for the electrolysis increases (and concomitantly the ammonia production rate), the higher the break-even time becomes. On the other hand, in moderately windy areas, it is more advantageous to invest in higher electrolyzer power (rated stack capacity) and focus on ammonia production.

The frequency of the excess renewable electricity production determines the economic feasibility of power-to-ammonia on a large national-scale. It was found, that power-to-ammonia at very large scale would have a reasonable chance for a successful business case only when approximately two times the planned 2020 renewable power is installed in the country. A wind- and solar-based power-generation with a nominal power of around 20.000 MW would be needed for increasing the yearly excess electricity production hours to a level where its distribution is uniform enough to economically operate a national scale power-to-ammonia plant powered exclusively by excess renewable electricity.

To increase the social acceptance of power-to-ammonia, the social and economic benefits of the technology and the way it is implemented has to be taken into account. The current ammonia technology is safe, but any power-to-ammonia plant should be realized at locations where as few people as possible experience any real or perceived safety risk. A dialogue with the public should be started in the very beginning of the planning process to create trust. The advantages and disadvantages of power-to-ammonia should be distributed at the community level as fairly as possible.

Samenvatting

Dit onderzoek is gebaseerd op de haalbaarheid van het power-to-ammonia concept. Hierbij wordt elektriciteit omgezet en opgeslagen in ammoniak. In deze studie wordt gebruik gemaakt van overtollig geproduceerde hernieuwbare elektriciteit voor de productie van waterstof en stikstof, dat uiteindelijk geconverteerd wordt naar vloeibare ammoniak. Hierbij wordt water en omgevingslucht door middel van electrolyse en drukwisselabsorptie gebruikt als grondstof. Door het gebruik van overtollig geproduceerde hernieuwbare elektriciteit kan het verschil tussen elektriciteitsvraag en aanbod gereduceerd worden waardoor de stabiliteit van het elektriciteitsnet zal toenemen. Dit concept resulteert in een duurzaam geproduceerde energiedrager door het gebruik van bewezen technologieën. Doordat ammoniak al geruime tijd wordt toegepast in verschillende sectoren is de benodigde infrastructuur reeds beschikbaar. Andere voordelen naast de bestaande infrastructuur zijn dat de opslag van ammoniak door de lage dichtheid eenvoudiger is dan bijvoorbeeld de opslag van waterstof of (vloeibare) methaan en dat er geen CO_2 emissies vrijkomen.

Het doel van dit onderzoek is om de technische, economische en maatschappelijke aspecten van het power-to-ammonia concept en de toepassing als flexibele energiedrager te analyseren.

Voor dit onderzoek zijn verschillende capaciteiten (van lokale schaal tot nationale schaal) bij diverse scenario's en op diverse locaties in Nederland onderzocht. Hiervoor is gebruik gemaakt van historische data van het KNMI (Koninklijk Nederlands Meteorologisch Instituut) om betrouwbare aannames te verrichten met betrekking tot de opbrengst van wind en zonne-energie.

De ammoniak-synthese is een continu proces dat op hoge druk met hoge temperaturen plaatsvindt. De opbrengst van overtollig geproduceerde energie fluctueert en dus ook de waterstofproductie door electrolysers. Daarom zijn voor de lokale schaal twee scenario's onderzocht zodat de installatie continu in bedrijfsvoering kan opereren: i) De toepassing van een waterstoftank als buffer voor de ammoniak synthese en ii) Elektriciteitsafname van het net indien

geen overtollige elektriciteit beschikbaar is. Op nationale schaal is alleen het scenario met waterstof-opslag onderzocht.
Als resultaat van dit onderzoek is gebleken dat het technisch haalbaar is om met duurzame energiebronnen en bewezen technologieën zowel waterstof als stikstof te produceren om deze vervolgens te converteren naar ammoniak. Door de wereldwijde toepassingsmogelijkheden en de reeds bestaande infrastructuur voor ammoniak heeft het concept een hoog potentieel als grootschalige energiedrager voor de toekomst met als bijkomend voordeel dat er geen CO_2 emissies zijn. Hierdoor biedt het concept perspectief voor de benodigde stabilisatie tussen vraag en aanbod van elektriciteit en zodoende kunnen de doelen betreft de Nederlandse energietransitie en CO_2 reductie voor 2020 worden gerealiseerd.

Vanuit bedrijfseconomisch oogpunt is op basis van gestelde operationele en investering kosten een inschatting gemaakt betreft de terugverdientijd van de verschillende scenario's. Uit de resultaten blijkt dat een power-to-ammonia plant met een elektriciteitsverbruik van 1,5 MW bedrijfseconomisch niet haalbaar is. De bedrijfseconomische haalbaarheid en daarmee een positieve businesscase blijken in Nederland realiseerbaar vanaf 15 MW (dus 10 keer zo veel). Daarnaast zijn, in verhouding met waterstofproductie, de kosten voor opslag en distributie van het ammoniak-concept aanzienlijk lager.

Verder blijkt dat voor het lokale scenario, waarbij geen overschot beschikbaar is en de plant op minimale belasting draait, het bedrijfseconomisch voordelen biedt om elektriciteit te importeren vanaf het net in tegenstelling tot het gebruik van een kapitaalintensieve waterstofopslag met de benodigde infrastructuur. Bij dit scenario geldt dat voor locaties met veel wind het voordeliger is om de elektriciteit te verkopen (rekening houdend met het verlies van overtollige energie), en daarmee de investering voor een power-to-ammonia unit te vermijden. Als de capaciteit van electrolysers stijgt en daarmee de hoeveelheid verkochte elektriciteit daalt, dan wordt de terugverdientijd namelijk hoger. Anderzijds is het in gebieden met minder wind voordeliger om de capaciteit van electrolysers te verhogen en daarmee de productie van ammoniak.

Voor het nationale schaal scenario wordt de economische haalbaarheid voor power-to-ammonia bepaald door de mate waarin overtollige energie beschikbaar is. Uit het onderzoek blijkt dat de power to ammoniak productie op deze grote schaal aanzienlijke kansen biedt indien de beschikbare hoeveelheid energie aanzienlijk hoger is. Een nominaal vermogen van 20.000 MW geïnstalleerde zonne- en- windenergie (dat is ongeveer tweemaal hoger dan de verwachte opbrengsten in 2020) zou nodig zijn op nationale schaal economisch een power-to-ammonia unit te bouwen die uitsluitend wordt aangedreven door een overschot aan elektriciteit.

Verder dient er rekening gehouden te worden met de sociale acceptatie van het power-to-ammonia concept. Ondanks de veilige technologie dient de plant op locaties gerealiseerd te worden waarbij zo weinig mogelijk mensen potentieel veiligheidsrisico oplopen. Het publiek zal daarnaast geïnformeerd moeten worden over de mogelijke gevaren en over de sociale en economische voordelen om het vertrouwen voor het concept te winnen.

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1. Introduction

1.1. Project background

This report is the result of the cooperation between Energy Valley, Hanze University of Applied Sciences and Proton Ventures BV within the TKI Power2X system integration subsidy program-line of the Netherlands Enterprise Agency (RVO). The work focuses on the feasibility of using ammonia as a flexible renewable energy carrier.

1.2. Renewable energy targets

The European Union has adapted emission reduction, energy savings and renewable energy targets for 2020 [1, 2]:

- A 20% reduction in EU greenhouse gas emissions from 1990 levels;
- Raising the share of EU energy consumption produced from renewable resources to 20%;
- A 20 % improvement in the EU's energy efficiency.

The European Union targets represent an important first step towards developing a low-carbon economy. They are as well headline targets of the Europe 2020 strategy for smart, sustainable and inclusive growth.

However, with only 5.5 % of energy generation coming from renewable sources in 2014, the Netherlands falls behind the other European countries (Table 1).

It is expected, that the percentage of renewable energy both in the Netherlands and in Europe will grow significantly in the coming decades. With the increase in the percentage of renewables in the countries, many new challenges for the reliability and performance of the existing power grid will occur. This comes as a consequence of the intermittency of renewable resources and the lack of large-scale economical storage capability.

Table 1. EU renewable shares, 2014 baselines and estimated 2020 targets [2, 1].

European country	Baseline % 2014	Target % 2020
Sweden	52.6	49
Latvia	37.9	40
Austria	33.1	34
Finland	38.7	38
Portugal	27	31
Denmark	29.2	30
Estonia	26.5	25
Slovenia	21.9	25
Romania	24.9	24
Spain	16.2	20
France	14.3	23
Italy	17.1	17
Netherlands	5.50	14
UK	7.00	15

1.3. The effect of renewable sources on the performance and reliability of the electric grid.

The growing renewable electricity sources in the Netherlands are wind and solar irradiation. These renewable electrical energy sources are integrated into the electric power system and the transmission grid at various voltage levels. The electricity gained from the renewable sources are certain to have a significant impact on the performance and the efficiency of the electrical grid. In order to avoid any power and system outages, the possible scenarios that can have an effect on the electric grids in the future have to be accordingly planned in advance.

One of the main challenges in the production of wind and photovoltaic electricity is caused by the significant mismatch between renewable electricity production and grid power demand. However, the rising penetration of renewables pose a dilemma. Wind and solar radiation are not always available when or where they are needed. Since power from wind and solar is variable, balancing supply and demand can be a problem. Therefore, new ways needed to be found to keep the system in balance and deal with all the excess energy. Our own calculations suggest (see details in Chapter 3) that installing around 10.000 MW nominal wind turbine capacity on a national scale (the 2020 target of the Dutch Government [3]) would produce excess electricity for a few times per year. The distribution and the number of these national excess hours depend on the weather pattern. However, as soon as the installed wind capacity approaches 15.000 MW, the excess production becomes more frequent (Figure 1) and would require a suitable means for large scale electrical energy storage.

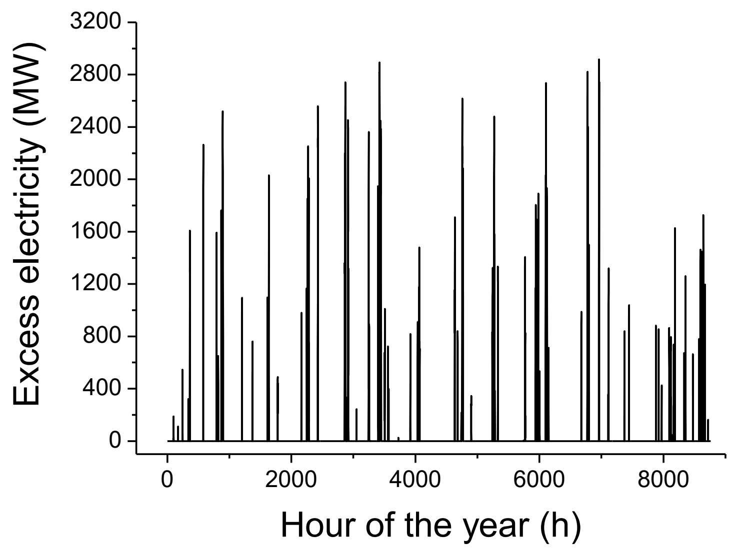


Figure 1. Excess electricity production on a national scale in a modeled scenario where 15.000 MW wind turbine capacity is assumed to operate in the Netherlands in 2014.

The electricity providing infrastructure can be divided into the transmission and the distribution subsystems determined by the different working voltage levels (Figure 2). The transmission subsystem, also known as the bulk power system, delivers electricity generated at central stations to locations close to load centers.

The Dutch transmission system consists of networks at 380, 220, 150 and 110 kV. The 380 and 220 kV networks are used for the longer distance transmission function while the role of the 150 and 110 kV can be defined as a sub-transmission function. The main body in the transmission network is a ring at the 380 kV voltage level with several radial branches, see Figure 2. In the Northern part of the Netherlands a similar ring structure exists at 220 kV level. In the western part of the Netherlands, the Randstad, a second and third 380 kV ring are implemented to fulfill energy demands while making sure that a certain level of supply security is reached [4].

In the Netherlands, TenneT, the transmission system operator (TSO), operates the 380 and 220 kV grids. The regional sub-transmission and distribution grids are operated by regional, distribution system operators (DSO).

The transmission grid in The Netherlands is connected to the neighboring countries, Germany and Belgium, through five interconnectors at 380 kV. In order to have more control over cross-border flows, phase shifting transformers were installed at the Dutch German border in Meeden. Furthermore, an additional high-voltage direct current link to England is in the early stage of development [4].

Figure 2. Overview of the Dutch high-voltage electrical system [5].

However, the increased development of the renewable power infrastructure in the neighboring and other European countries will inevitably lead to situations where the problem of an excess electricity production could not be solved by simply transporting it to other regions. Research studies showed that worldwide electricity demand was fulfilled with the installed renewable power capacity at the end of 2013, whereas by 2050 the demand can be overtaken with an additional excess energy [6, 7, 8].

With upcoming targets in the renewables and new regulations accepted in Paris Climate Change Conference regarding CO_2 emissions, finding solutions to deal with the generated excess electricity is a growing concern. The Netherlands together with other European countries has adopted European climate and energy measures as well as agreeing on common EU positions in the global context. The Netherlands committed to achieve a 20 % reduction in EU greenhouse gas emissions from 1990 levels till 2020 and at least 40 % greenhouse gas reduction in 2030 to a robust and effective legislative framework [2, 9]. The Dutch government considers that it is essential to fully integrate a growing supply of renewable energy into the EU energy system. For the Netherlands up to 2020 this means the following [9]:

- A non- Emissions Trading System share of 16 % (binding);
- 14 % renewable energy (binding);
- 1.5 % savings per year.

In order to achieve the set targets and to deal with this issue, a strategy needs to be employed aiming to exploit the excess energy, stabilize the grid and reduce the greenhouse gas emission. A possible solution for this issue is power-to-ammonia, a chemical energy storage technology at wind turbine locations. This concept uses the produced excess electricity to electrolyse water, and then react the obtained hydrogen with nitrogen, where the nitrogen is produced through air separation. The product, ammonia, would serve the purpose of storing the excess renewable energy.

Ammonia offers an attractive chemical storage option for renewable power since:

- ammonia plants are scalable to gigawatt-hour sizes;
- ammonia can be stored for long periods of time;
- a mature global infrastructure already exists; and
- ammonia is an industrial chemical that can be used further either as a fuel, fertilizer, de-NOX agent and chemical commodity.

Moreover, at this moment, one of the additional problems, not directly linked to the new perception of the future grid stabilization, is the amount of greenhouse gases that are emitted from the ammonia industry, since hydrogen production is almost exclusively based on fossil feedstocks. Natural gas in the Western Europe releases 2.34 metric tons of the greenhouse gas carbon dioxide, respectively, for every metric ton of produced ammonia [10, 11, 12, 13]. A more environment-friendly option would be to produce the hydrogen via water electrolysis powered by renewable electricity.

2. System integration of power-to-ammonia

2.1. Technical benefits of an electrical energy storage system

Energy storage will play a key role in enabling the EU to reach the promised targets of emission reduction and increase of the renewable energy which will have effect on the grid stability and it's operation. Energy storage can supply more flexibility and balancing to the grid, providing a back-up to intermittent renewable energy. Locally, it can improve the management of distribution networks, reducing costs and improving efficiency. In this way, it can ease the market introduction of renewables, indirectly increase CO_2 reduction, improve the security and efficiency of electricity transmission and distribution (reduce unplanned loop flows, grid congestion, voltage and frequency variations), stabilize market prices for electricity, while also ensuring a higher security of energy supply.

Additionally to the grid stabilization during the grid disturbance, energy storage technologies can also be used to support the normal operations of the grid. Four types of support operations can be performed through the use of an energy storage application [14, 15, 16]:

- Frequency Regulation Services: The storage system can be used to provide and absorb power to maintain grid frequency in the face of fluctuations in generation and load.
- Unforeseen Reserves: At the transmission level, an unforeseen reserve includes spinning (or synchronous) and supplemental (non-synchronous) reserve units, and they provide power for up to two hours in response to a sudden loss of generation or a transmission outage.
- Voltage Support: Voltage support involves the injection or absorption of reactive power (VARs) into the grid to maintain system voltage within the optimal range. Energy storage systems use power-conditioning electronics to convert the power output of the storage technology to the appropriate voltage and frequency for the grid.
- Black Start: Black start units provide the ability to start up from a shutdown condition without support from the grid, and then energize the grid to allow other units to start up.

A properly sized energy storage system can provide black start capabilities, provided it is close enough to a generator.

2.1.1. Power quality and reliability

The most often adopted reason of electrical energy storage is to use it in order to improve the power quality and reliability. The most common issues of grid-related power quality events are voltage sags and interruptions with durations of few seconds [17].

2.1.2. Load shifting

Storing excess electric energy during periods of low demand and releasing the stored energy during periods of high energy demand is the main concept behind load shifting. The most common form of load shifting is peak shaving, when the energy storage system is used to reduce peak demand in an area [18]. Peak shaving is usually applied when the peak demand for a system is much higher than the average load. This allows an utility to defer the investment required to upgrade the capacity of the network. From an economic point of view the economic viability of peak shaving depends mostly on the rate of load growth and on the price differential between minimum and maximum price [18].

2.1.3. Supporting the integration of intermittent renewable energy sources

After hydropower, wind power generation is the next largest sustainable energy source and presently the fastest growing renewable power source in the world [19, 20]. Wind energy has been used since the earliest civilizations to pump water, power sail boats and grind grain.
In the last decades, industry has been developing the approach where wind turbines would be used to convert power from wind to electricity. The following applications of an energy storage system can be applied in supporting the integration of wind power [21]:

- Frequency and synchronous spinning reserve support: If there is a significant amount of wind generation in the grids, intermittency and variability in wind generation output due to sudden shifts in wind patterns can lead to significant imbalances between generation and load that in turn result in shifts in grid frequency. These imbalances could be managed by applying a spinning reserve at the transmission level. A storage system can provide quick response to such imbalances without the emissions related to most conventional solutions.
- Transmission-decrease reduction: Wind turbines are mostly built in remote areas where transmission and distribution systems are less developed. As a result, wind operators are forced sometimes to reduce their production and therefore lose production opportunity, or are required to invest in the expansion and upgrading of the transmission network. An energy storage system coupled to wind turbines can store the excess energy and furthermore deliver it at times when the transmission system is not overloaded.
- Time Shifting: Wind turbines are renewable energy sources that cannot adjust their power output accordingly to an order or demand at the request of grid operators. A storage system can be used to store energy generated during periods of low demand and deliver it during periods of high demand. When applied to wind generation, the commonly used term is “firming and shaping” because it changes the power profile of the wind to allow greater control over dispatch [22].

Similar applications also exist for renewable energy sources other than wind power, such as solar photovoltaic (PV), though typically at a lower scale, and less centralized.

2.1.4. Power-to-X concept as a cost reduction approach

From an economical point of view, power-to-x technology can enable companies to achieve the emission reduction ($C0_2$ reduction and increase of the renewable sources) in a more cost-effective way. An example can be found in the neighboring country Germany where Fraunhofer Institute for Solar Energy Systems ISE revealed a study on role of power-to-gas in achieving policy targets [23]. From their overview and analysis, it can be seen that an extensive reduction in carbon dioxide emissions would reduce the total annual costs of the German energy system by billions of euros per year, if an electrical energy storage is adopted and developed accordingly in the future. If carbon dioxide emissions are reduced by 75 to 82 % in 35 years with the approach of power-to-x technology, this would lead to a significantly lower economic cost. The study was based on a simulation model for the current cost-optimized sustainable energy supply in Germany, which was further differentiated for the analysis [23].

2.2. Power-to-Ammonia

In an electrical system, supply and demand have to be balanced on a per-second basis. Electricity production, especially renewable sources, cannot be increased so fast. Therefore, sufficient power should be supplied to the system in order to be able to meet the maximum electricity demand. The maximum consumption is only reached for a few hours per year (the average demand is ~60 % of maximum demand). To manage these fluctuations, demand side management technologies (balancing the supply of electricity) in combination with energy storage can be used to operate the electricity system normally.

A number of electricity storage technologies are used nowadays. Figure 3 shows an overview of the most common storage technologies. Generally, these technologies can be divided into direct and indirect storage technologies. In direct technologies the electricity is stored in the magnetic or electrical field of a capacitor or inductor. In case of indirect technologies the electricity is stored in mechanical (potential, kinetic etc.) or chemical energy and it is converted back into electricity when needed.

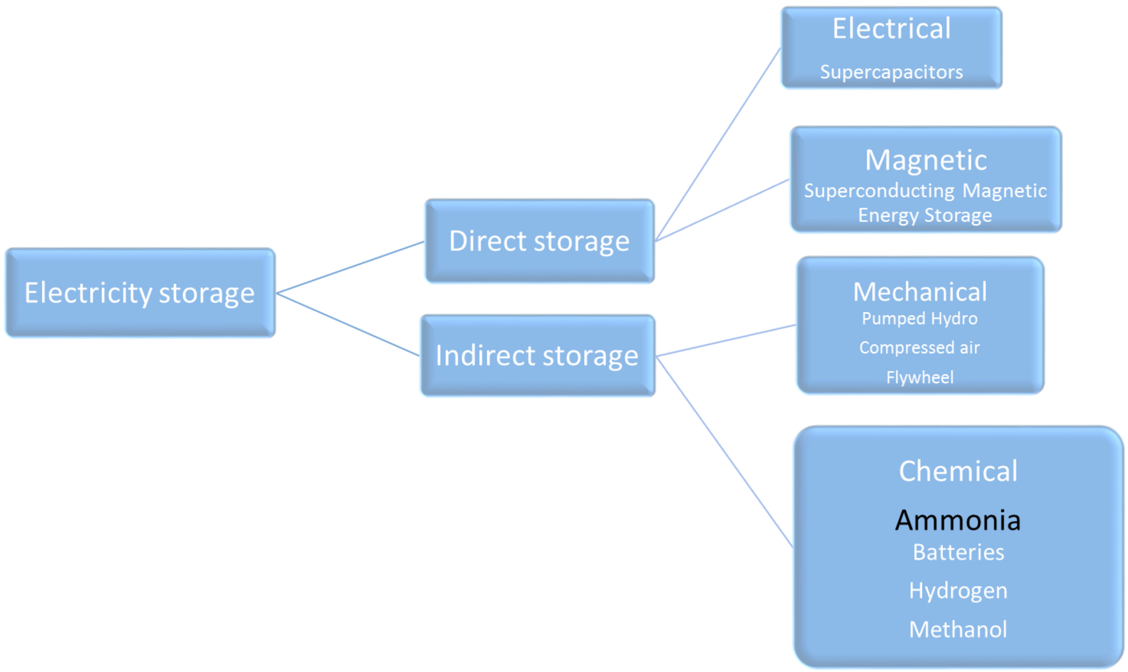


Figure 3. Overview of electricity storage systems [24].

"Power-to-ammonia systems'' produce ammonia through the use of excess renewable electricity from wind turbine generators or solar panels. Wind turbines are commercially available in sizes up to about 2.5 MW of nominal capacity for on-shore applications and even larger (3.7 MW) can be found in off-shore applications. The electrical output of the wind turbine is dependent on the wind speed and availability, resulting in unpredictable electrical energy production variations. The "green" ammonia synthesis is designed to use as a base a renewable energy-powered electrolyzer to produce hydrogen from water and an air separation unit to obtain nitrogen from air. Both materials are further used as reactants in a Haber-Bosch synthesis reactor for the production of ammonia (Figure 4).

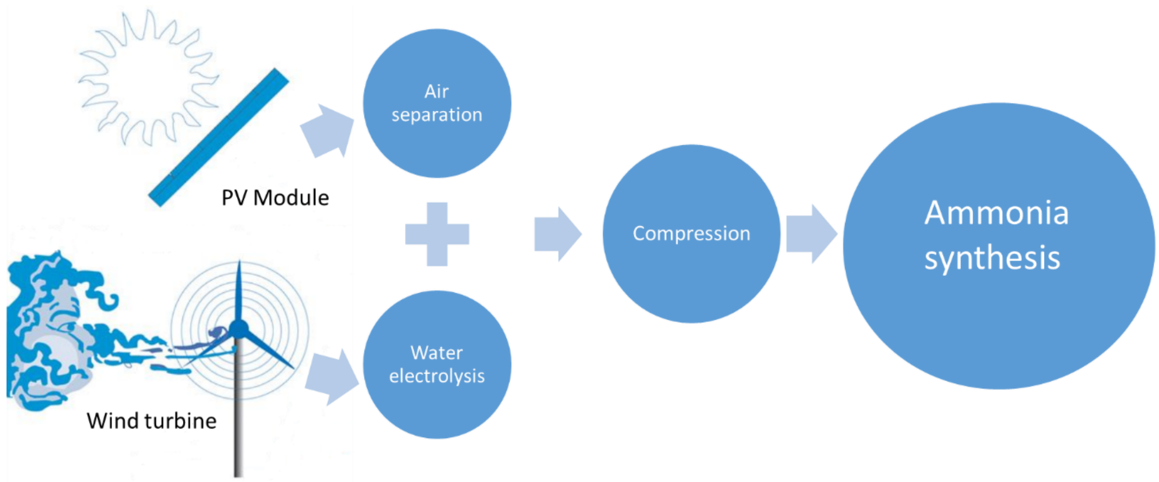


Figure 4. Overview of electric (wind or PV) powered ammonia production process.

2.3. Renewable ammonia production

2.3.1. Hydrogen production through water electrolysis

In periods of excess electrical energy production, the electrolyzer is switched on, and water is decomposed into hydrogen and oxygen. Due to the low input voltage of an electrolyzer it is necessary to decrease the high output voltage of the grid with the help of an AC/DC converter equipped with a step-down isolation transformer. The hydrogen generation system consists of two main parts:

1. Interface AC/DC converter with a step-down isolation transformer, which allows interfacing the high voltage AC output of converter with a low voltage input of the electrolyzer.
2. Electrolyzer, which produces hydrogen from water using excess electricity from the wind generator. There are three basic types of electrolyzers: alkaline, proton exchange membrane (PEM) and high-temperature solid oxide electrolyzers (SOEC) [25]. The key operational parameters of the three electolyzers are summarized in Table 2.

Table 2. Summary of the key operational parameters of the currently available electrolyzers [26].

	Alkaline	**PEM**	**Solid oxide**
State of development	Commercial	Commercial	Laboratory
H_2 production, m^3/h	<760	Up to ≈ 450	-
Electrolyte	Alkaline solution	Solid polymer membrane	ZrO_2 ceramic doped with Y_2O_3
Charge carrier	OH^-	H_3O^+/H^+	O^{2-}
Cell temperature °C	40-90	20-100	800-1000
Cell voltage V	1.8-2.4	1.8-2.2	0.91-1.3
System power consumption kWh/m^3	4.5-8.2	5.2-7.1	-
Cold start time	Minutes-hours	Seconds-minutes	-
Advantages	Available for large plant size, cost, lifetime	No corrosive substances, high power density, high pressure, dynamics	High electrical efficiency, integration of waste heat possible,
Disadvantages	Low current density, maintenance cost	Expensive, fast degradation	Limited long term stability of the cells, not suited for fluctuating systems, expensive,
Lifetime	Up to 30	5	-
System costs €/kW (average) [27]	1100	2090	-

The alkaline electrolyzer suppliers currently dominate the water electrolysis market with a broad stack capacity range and varying system energy requirements. Commercial PEM system suppliers are on the rise, but system sizes are still below the MW scale. No commercial SOECs are currently available [27]. The current density and deployment time from standby are important aspects for the flexible operational use in power-to-ammonia.

2.3.2. Nitrogen production

Three methods exist for obtaining pure nitrogen gas: cryogenic distillation, polymer membrane separation and pressure swing adsorption (PSA). Cryogenic nitrogen purification constitutes around 90 % of all commercial production [28] today. In addition, combustion can be used to eliminate oxygen from the air either in a reformer or in a combustor. Table 3 shows the composition of dry air.

Table 3. Principle gases of dry air [28].

Constituent	Percent by volume
Nitrogen – N_2	78.084
Oxygen – O_2	20.946
Argon – Ar	0.934
Carbon dioxide – CO_2	0.034
Neon - Ne	0.00182
Helium - He	0.000524
Methane – CH_4	0.00015
Krypton – Kr	0.000114
Hydrogen – H_2	0.00005

Figure 5. Summarizes the ranges of the nitrogen separation technologies. This figures is based on two most important parameters: nitrogen purity and its flow rate. For example for a specific purity and flow rate, one may suggest the membrane system (shown in the graph as permeation) as the most economic choice while the other presents PSA process as the best one (shown in the graph as adsorption). The purity for nitrogen supply to the ammonia production section is very much limited by the catalysts in the ammonia reactor system, where usually very low levels of oxygen components can be allowed. Different ammonia technology suppliers (like Proton Ventures BV) can handle higher amounts of oxygen components and therefore can use cheaper N_2 generation processes.

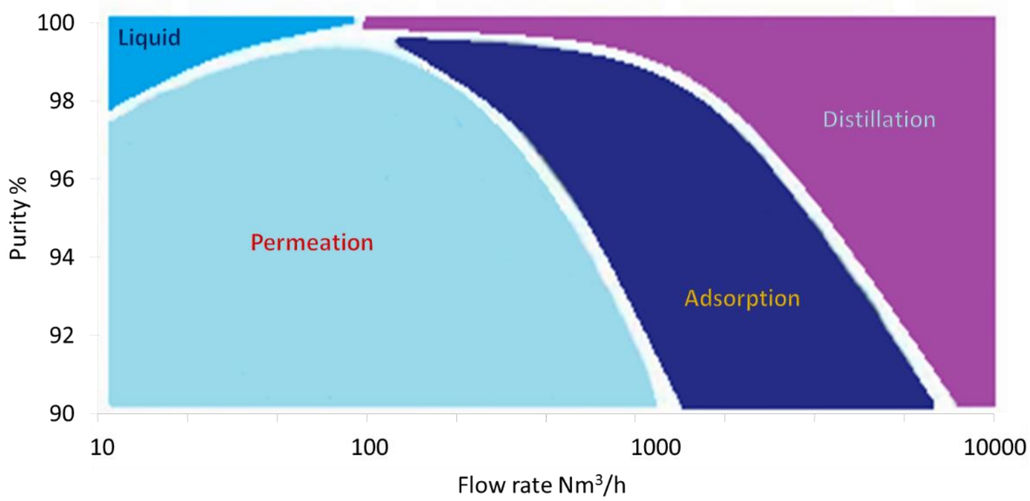


Figure 5. Selection Diagram for nitrogen production process [28].

Cryogenic air separation

Cryogenic air separation exploits the boiling point difference in the three main constituents of air – nitrogen, oxygen and argon (Table 3) [29]. The process shown in the Figure 6 consists of:

- Compression and cooling of air
- Purification of dry air stream
- Cooling of the air up to the dew point of air (-176.15 °C)
- Distillation of air

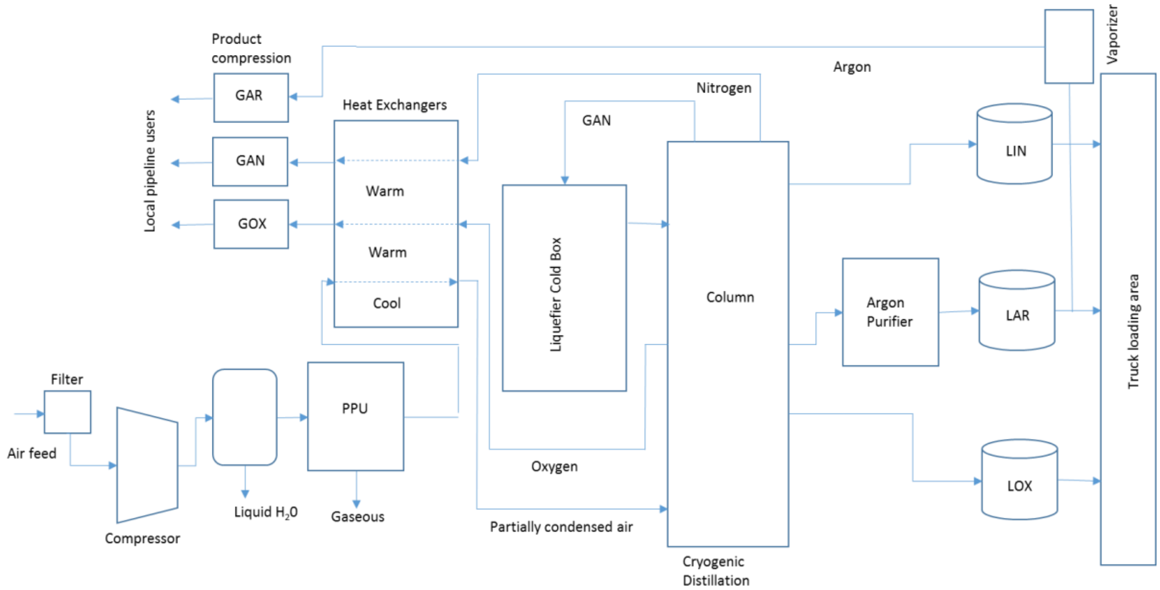


Figure 6. Cryogenic air separation [30].

Pressure swing adsorption

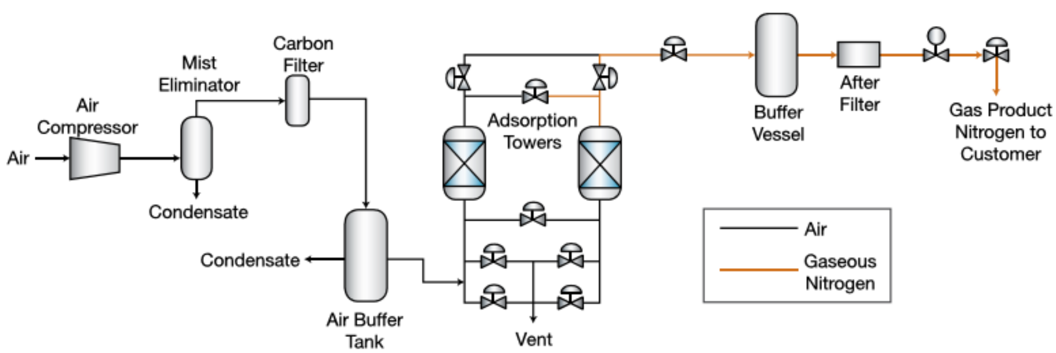


Figure 7. Pressure swing adsorption process configuration [31].

In a PSA process compressed air first passes through a combination of filters. The purified air is then directed to one of the two adsorption vessels that are packed with adsorptive materials (zeolite, activated carbon, etc.). The impurities, such as carbon dioxide and residual moisture, are adsorbed by the carbon molecular sieves at the beginning of the adsorbent bed. At high pressures, the carbon molecular sieves selectively adsorb oxygen, allowing nitrogen to pass through at the desired purity level. The automatic cycling of adsorption and desorption between the two beds enables the continuous production of nitrogen (Figure 7) [31].

Membrane separation

This system operates on the principle of selective gas permeation. A typical membrane process (Figure 8) uses several membrane modules. Every molecule has a characteristic permeation rate that is a function of its ability to dissolve in, diffuse through, and dissolve out of the hollow-fiber membrane.

When compressed air passes through the fibers, oxygen, water vapor, and carbon dioxide are selectively removed, creating a nitrogen [32].

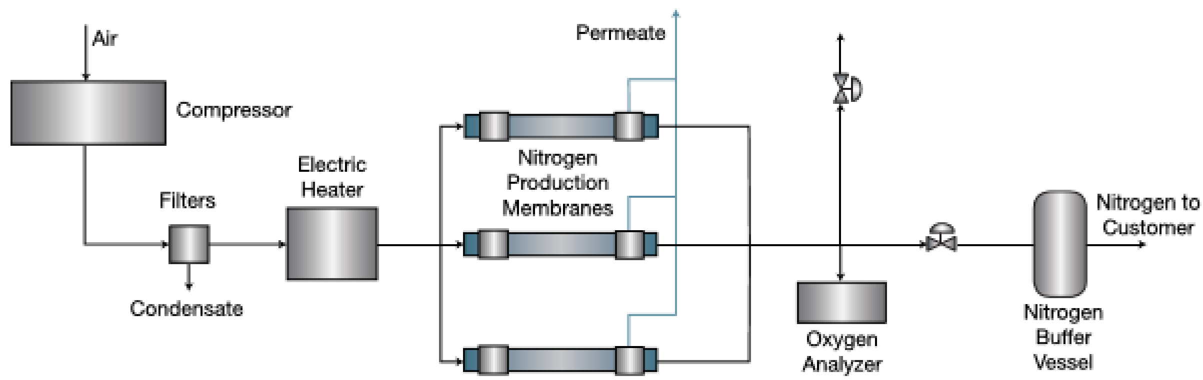


Figure 8. Membrane system for nitrogen generation [32].

2.3.3. Ammonia synthesis through the Haber-Bosch process

In the ammonia plant, the hydrogen and nitrogen, after being produced, are mixed to form a syngas with a ratio of 3:1 respectively. Nitrogen and hydrogen react at 350-550 °C and 100-300 bar over an iron-based catalyst. The reaction is exothermic and generates 91.4 kJ/mol heat. Due to low conversion of the syngas feed to ammonia, commonly 15-30 %, a large share of the stream leaving the reactor consists of unconverted syngas. To separate the ammonia from the syngas components for the refrigeration. The condensed ammonia is removed and the residual syngas is recycled as reactor feed [33].

2.4. Storage of ammonia

Ammonia is a liquid when compressed or cooled. It is stored under pressure to prevent vaporization so a large volume can be available for use. For pressure vessels, the inspection requirements in most countries are governed by the respective pressure vessel codes and regulations.

Two main methods exist for storing liquid ammonia [34]:

1) Pressurized storage at ambient temperature in spherical or cylindrical pressure vessels having capacities up to about 8000 t (Figure 9 a)).
2) Atmospheric storage at – 33 °C in insulated cylindrical tanks for commonly amounts around 10 000 t per vessel (refrigerated).

The illustrations of the different types of storage tanks are shown below. The main types of atmospheric tanks operating at -33°C in Europe are [35]:

a. Steel tank with full height concrete bund wall close to it with capacity to contain the full contents of the tank and the space between the tank and the bund having an impervious floor and roof covering (Figure 9 b)).
b. Steel tank housed within another steel tank to contain the full contents of the tank, with a single roof (cup in tank) or independent roofs (Figure 9 c)).
c. Steel tank with a partial height concrete bund wall with impervious floor within the contained area and no roof over the space.
d. Steel tank with an embankment of earth to contain the full contents of the tank and no roof over the space between the tank and the embankment.
e. Single steel wall tank with no secondary containment.

a) b) c)

Figure 9. Storing liquid ammonia; a) pressure storage at ambient temperature; b) and c) refrigerated storage (BCT terminal, Estonia) [34].

In some cases, ammonia is also stored at intermediate temperatures and pressures (semi-refrigerated). For pressure vessels, the inspection requirements in most countries are governed by the respective pressure vessel codes and regulations [36]. The cost of storage mostly depends on the use of the available infrastructure. The capital costs of ammonia storage tanks are related to the amount of steel required. For high pressure storage, about 2.8 tons of ammonia can be stored for every ton of steel, whereas for low temperature storage over 40 tons of ammonia can be stored per ton of steel [34].

In the Netherlands two main ammonia producers are considered to be Yara and OCI Nitrogen. As an example, OCI Nitrogen has two world-scale production plants at Geleen, The Netherlands, with effective capacities of 560 000 tons and 570 000 tons/year, respectively [37]. The ammonia produced in Geleen is stored in two atmospheric cooled tanks, each containing 25 000 m^3. At the Geleen site, ammonia is supplied through a liquid ammonia distribution grid to which the ammonia storage tanks are connected. Supply to external customers is arranged through leased rail cars that directly connect the Geleen site to customer's production sites. The Geleen site has fully integrated rail loading facilities and a daily loading capacity of 24 rail tank cars. Moreover, OCI Nitrogen is the owner of two ammonia storage tanks at Europoort (Rotterdam) shown in the Figure 10. Each tank has a capacity of 15 000 tons of refrigerated ammonia [37].

Figure 10. OCI Nitrogen – two ammonia storage tanks at Europoort (Rotterdam)

2.4.1. Comparison of energy carriers

Many different materials can store energy, ranging from wood, to gas, to uranium. These materials are known collectively as fuels, and all of these fuels are used as energy sources for a variety of systems. Some fuels can be considered as energy rich carriers. The amount of energy that can be stored in energy carriers, in a given mass of a substance or system is related as an energy density [38]. Furthermore, the use of fossil fuels in the transportation sector have resulted in a greenhouse gas emissions. Therefore with agreed points from Paris Climate Change Conference regarding CO_2 emissions, there is a strong need to come up with some environmentally benign and sustainable alternatives. In general when comparing the energy carriers, the higher the energy density of a system or material, the greater the amount of energy stored in its mass. Energy can be stored in many different types of substances and systems (Figure 11).

Figure 11 shows the comparison of power density and energy density of different storage technologies and energy carriers.

In this regard, the volumetric energy content of the fuel is considered an important parameter because it accounts not only for the calorific value, but also for the fuel ability to perform work due to pressure difference between the tank pressure and environment. For a given amount of energy, the higher the power and energy densities are, the smaller the volume of the required energy storage system will be. From the Figure 11 it can be seen that ammonia has a both lower volumetric (11.5 MJ/L) and gravimetric density (18.6 MJ/kg) compared to other energy carriers except hydrogen. Compared to other fuels, diesel stores the most energy per unit of volume (34 MJ/L). However, diesel has the disadvantage that when combusted in an ICE emits SOx, NOx, large amounts of CO_2 and other pollutants. Furthermore, liquid hydrogen has a higher gravimetric energy density (MJ/kg) than ammonia but a lower volumetric energy density (8 MJ/L) as shown in Figure 11. The low energy density of hydrogen, both when liquefied and at high pressure, presents a storage challenge for vehicular applications, as well as large scale hydrogen storage, making ammonia more viable and attractive option [39]. Regardless the lower energy densities, compared to other fuels such as diesel and gasoline, ammonia releases little or no greenhouse gas when burned, and that it's possible to produce it by means that involve minimal GHG emissions throughout its lifecycle [40].

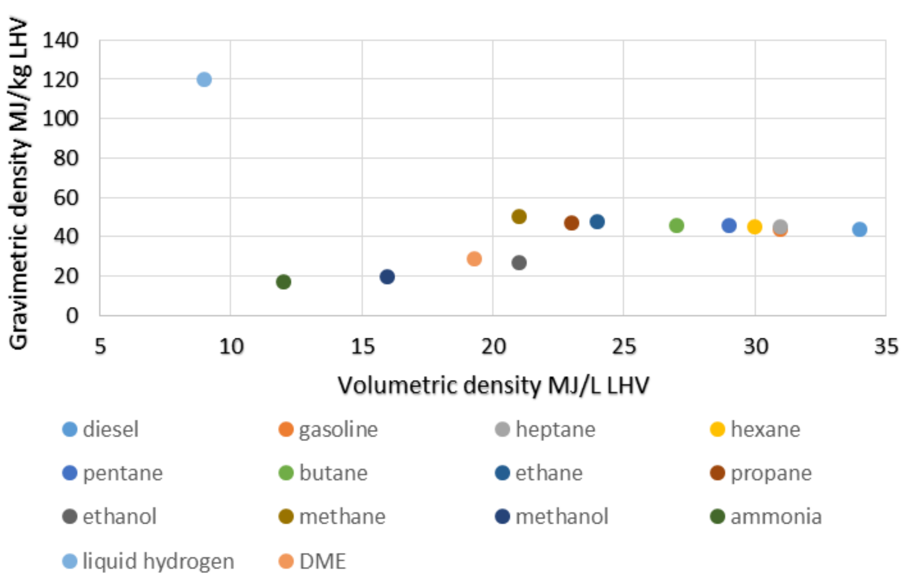


Figure 11. Volumetric and gravimetric energy densities of various energy carriers.

Figure 16 compares the cost of storage for ammonia and hydrogen per unit of delivered energy. Additionally, the size of the storage devices is an important factor for many applications.
An anhydrous ammonia transport tank, even with a 4.5 times smaller volume, stores 31 % more H_2 mass than a pressuried hydrogen transport tank (Figure 12) [39].

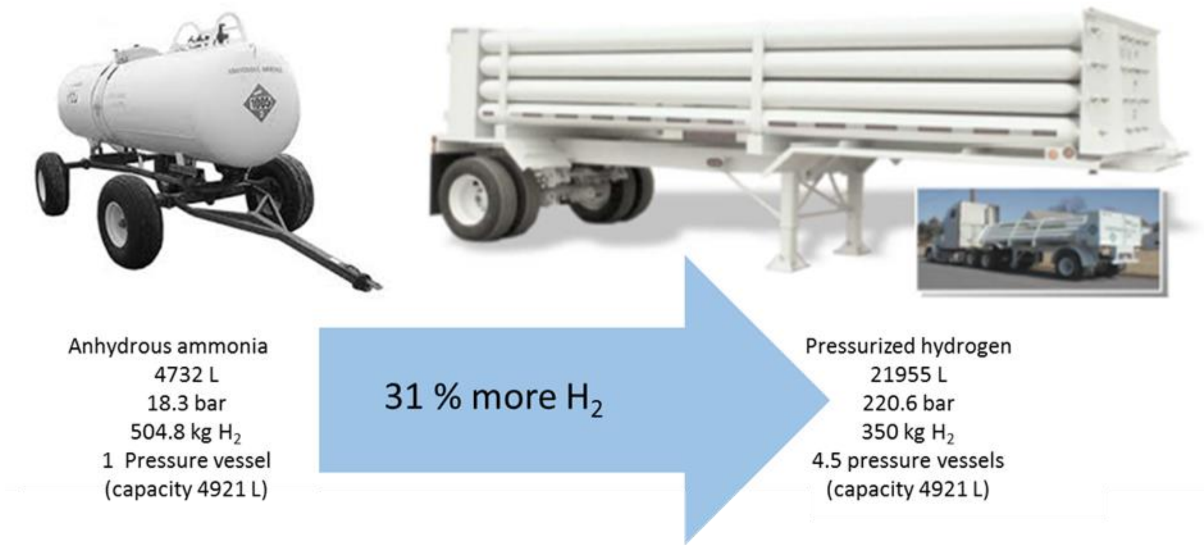


Figure 12. The storage capacity comparison of anhydrous ammonia and pressurized hydrogen tanks [39].

2.5. Transport of ammonia

Ammonia is used as a base chemical for a large number of intermediate products that find their use in many applications. As a result of the international market and high demand for ammonia, ammonia can only be produced economically in large scale production plants. If an industrial site has an ammonia consumption that is a lot smaller than the economical size of an ammonia plant, it is required to transport the ammonia to this site. Rail transport is regarded as a safe means of transport for large quantities of ammonia [37].
In the Netherlands, ammonia is produced from natural gas in the industry located in Geleen and Sluiskil (Figure 13). Part of the produced ammonia in Sluiskil is further exported along the Westerschelde as well as through Westerschelde to companies in Antwerp. Ammonia in Geleen

and IJmuiden Sluiskil is partly processed into fertilizers. For fertilizer production in IJmuiden ammonia is imported from Geleen by rail. Ammonia is used as a raw material by many chemical companies in the Netherlands. The ammonia for these companies is transported by rail from Geleen (Figure 15). Figure 13 shows the balance of production and distribution of ammonia in the Netherlands in the form of the Sankey diagram [41]. Production location and the most important delivery (customer) points are also indicated in Figure 14.

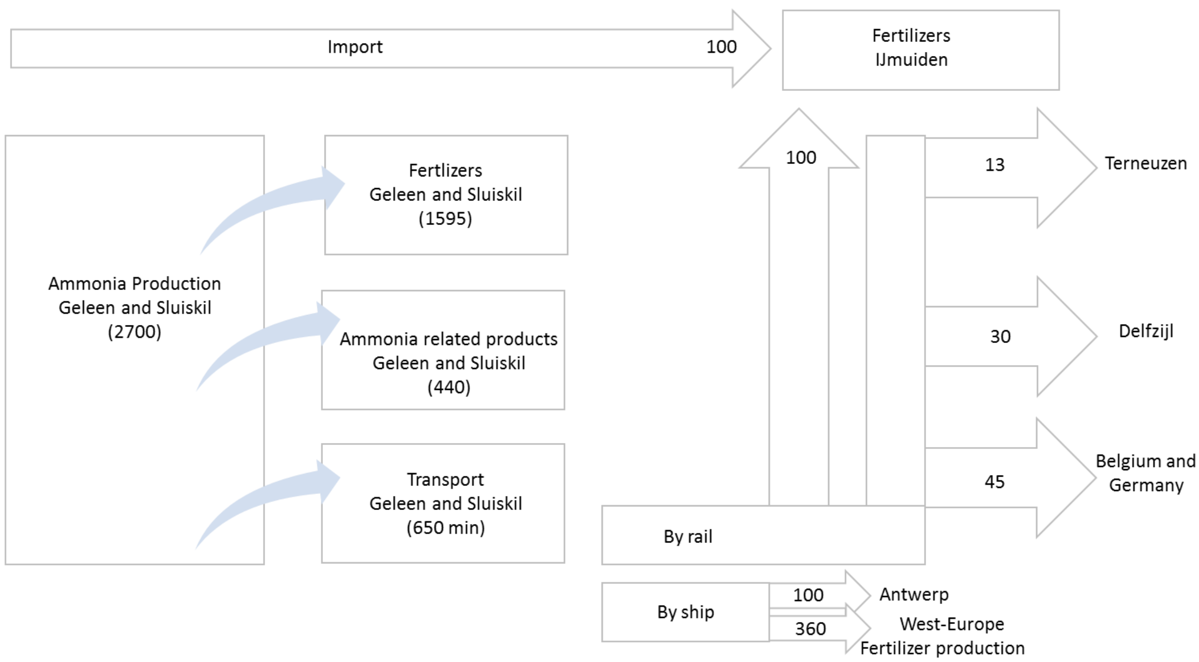


Figure 13. Production and distribution of ammonia in The Netherlands (quantities expressed in 1000 ton).

In the UN classification system for transport, anhydrous ammonia and strong solutions of ammonia are classified as toxic gas of Division 2.3, falling in Class 2 [36]. Dilute solutions fall in Class 8, corrosive substances. Table 4 summarizes the relevant particulars. The UN transport regulations specify a proper shipping label for all the dangerous substances. This also applies to mixtures and solutions. The proper shipping labels to be filled in the accompanying documents are also shown in Table 4.

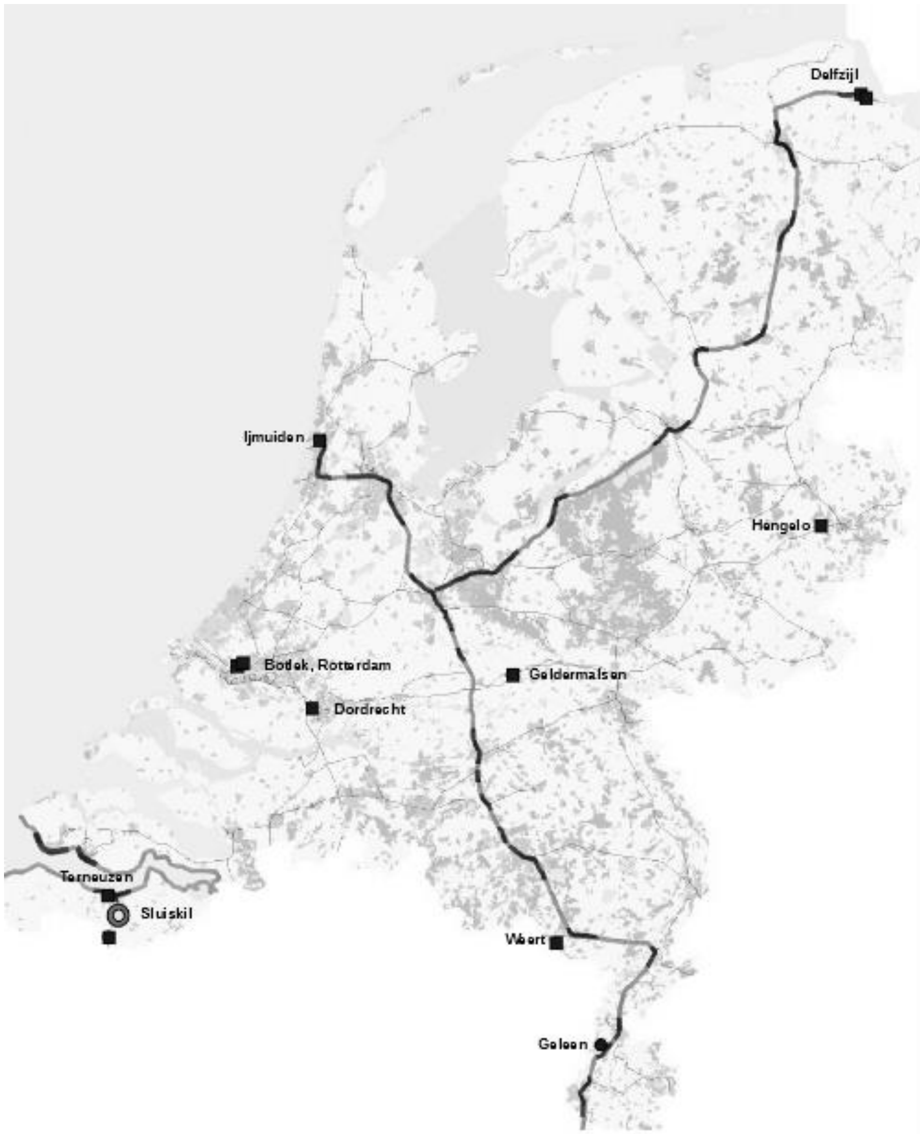


Figure 14. Locations in the Netherlands of ammonia producers (●); delivery points (customers) (■) and transport routes by rail [41].

Figure 15. Rail transport of ammonia in Netherlands (source OCI).

Table 4. UN transport classification and labeling [42].

UN no.	Name and description	Class	Labels	Tank code	Transport category	Hazard identification number
1005	Ammonia anhydrous	2	2.3+8(+13)	PXBH(M)	1	268
3318	Ammonia solution relative density less than 0.880 at 15°C in water, with more than 50 % ammonia	2	2.3+8(+13)	PXBH(M)	1	268
2073	Ammonia solution relative density less than 0.880 at 15°C in water, with more than 35 % but not more than 50 % ammonia	2	2.2(+13)	PXBN(M)	3	20
2672	Ammonia solution relative density less than 0.880 and 0.957 at 15°C in water, with more than 10 % but not more than 35 % ammonia	8	8	L4BN	3	80

Ammonia is classified as a "hazardous substance" and transport, as previously mentioned, is subject to stringent safety requirements. Ammonia is often transported by rail, and the fact that routes in the Netherlands pass through city centers involves risks. Therefore there is need to minimize rail transport of ammonia as far as possible. Ammonia is transported via the routes in the "basic rail network for the transport of hazardous substances", for example the Betuwe line [43].

The alternative forms of ammonia transport include pipeline, large sea-going vessels, river barges, rail tank cars and tank trucks (except in Germany). Inside Europe ammonia is transported by river barges, rail tank cars and tank trucks. In Europe there are no long-distance pipeline systems. The most comparable transport form for large quantities versus rail tank cars is river barges. The locations that need to import ammonia are not necessarily located next to a canal suitable for river boats. The advantage of rail tank cars is that they can reach more locations, however the transferred load per rail tank cars is considerably less than for river boats [42].

3. A comparative evaluation of the available electrical energy carriers

This chapter presents static data and characteristics of different technologies that are available for electricity storage. The technologies discussed here are: power-to-chemicals (ammonia and methanol), power-to-gas (hydrogen, methane), compressed air energy storage, flywheels, supercapacitor and batteries. The detailed description of the mentioned energy storage technologies is out of the scope of this study. Instead, a brief overview of the latest developments and potential disadvantages are given here. In order to provide a more complete picture of the entire portfolio on future energy storage technologies see tables 5 and 6.

- Flywheels store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor; during discharge, the same motor acts as a generator producing electricity from the rotational energy of the flywheel. They have several disadvantages including their low energy and power density, large standby losses, and potentially dangerous failure modes [44]. They are not suitable for storing energy for more than a day (they have a self-discharge rate of 3-40 % per hour), they have a low energy capacity (less than 25 kWh). Flywheels are relatively expensive, and their application is limited to frequency control, reactive power mediation and possibly short-term uninterruptible power supply [45].

- Batteries are electrochemical devices that convert chemical energy into electrical energy during battery discharge. While primary batteries lose all of their electricity when the chemical reactions are spent, secondary or rechargeable batteries can reverse the chemical reaction by the introduction of electricity. The fundamental building block of a battery is a single electrochemical cell, which generally consists of two different electrodes and an electrolyte [45]. Many different battery types exist today. However, different forms of batteries are suitable mostly for short term applications.

- Compressed Air Energy Storage (CAES) system compresses a gas (usually air) to high pressures (70 to 100 bar) and injects it into either an underground structure (e.g. cavern, aquifer, or abandoned mine) or an above ground system of tanks or pipes to store energy. This kind of system has several disadvantages. It requires a suitable site that must satisfy specific underground geological characteristics. Large subterranean caverns of suitable geologic strata, ancient salt mines, or underground natural gas storage caves are ideal for CAES as they can maintain high geostatic pressures with minimal loss [46]. The underground caverns must be large enough to make CAES cost effective [47]. The air must be heated when it is decompressed and this heat is typically derived from combusting natural gas, which greatly reduces the efficiency of the overall system. Each kilowatt-hour of stored compressed air would require 4500 kJ of fuel for heating. Lastly, CAES systems generally have a long construction time.

Unlike above mentioned storage technologies, ammonia as an energy storage technology is suitable for mid-term or long-term storage. Ammonia can be easier liquefied than other gaseous energy carriers such as hydrogen and methane, making it easier to store and transport. This is a significant advantage, because it could be transported in tankers or pumped over existing gas pipelines. Although it is toxic, its characteristic smell would quickly give away the presence of leaks. Hydrogen, stored at higher pressures, is likely to be more dangerous [48].
Furthermore, the performance and characteristic parameters of some technologies that store energy in chemicals are summarized in table 5.
Comparing hydrogen to ammonia, there are several disadvantages to hydrogen storage systems. First, the storage cost of hydrogen is quite high given current technology. Lastly, analyses of the full life cycle cost for hydrogen storage systems have not yet been performed [52].

Table 5. Chemicals that could be used as renewable energy storage materials.

Energy carrier	Energy density Wh/L	Power density W/L	Specific energy Wh/kg	Suitable storage duration
Ammonia	4325 [49, 50, 51]	4325 [49, 50, 51]	4318-5140 [49, 52]	Hours-months
Hydrogen	2600 [52]	2600 [52]	33300 -39000 [52]	Hours-months
Methane	6400	6400	15400	Hours-months
Methanol	4600	4600	5600-6400 [52]	Hours-months

It is apparent that the energy application is the key to determining which storage technology is most suitable for a given situation. Every storage technology is defined by the storage properties, and these properties will further determine which storage technology is most suitable. Based on which application the stored energy is intended to be used for, one can easily judge which technologies best meet their needs and should be studied further (Table 6).

Table 6. Technology suitability of various energy storage technologies [45].

Technology Name	Frequency Control	Hourly Balancing	Daily Balancing	Seasonal Balancing	T&D Congestion Relief	Black Start	Off-grid / Micro grid	Waste Heat Utilization	Off- to On-Peak Shifting & Firming	Demand Shifting & Peak Reduction	Energy Arbitrage	Reactive Power	Uninterruptible Power Supply	Transport
Electric Energy														
Pumped Hydro	●	●	●	○	○	◐	○	○	◐	○	●	●	○	○
Compressed Air Energy Storage	●	●	●	○	○	◐	○	○	◐	○	●	◐	○	○
Lead Acid Battery	○	●	○	○	◐	●	●	○	◐	●	○	○	●	●
Lithium Ion Battery	○	●	○	○	◐	●	●	○	◐	●	○	○	●	●
Gas and Liquid Fuel														
Hydrogen Gas	●	●	●	●	●	○	○	○	◐	○	●	◐	○	◐
Liquefied Natural Gas	○	●	●	○	◐	○	○	○	○	○	○	○	○	○

● indicates full suitability

◐ indicates potential or moderate suitability

○ indicates no suitability

3.1. The cost of power-to-X technologies

This chapter focuses on the economics/costs of only the power-to-x-energy storage technologies using ammonia, methane and hydrogen as storage materials. Generally, the costs of a power-to-x plant can by divided into capital cost for the construction and variable cost for the operation of the unit (Table 7).

Table 7. Total costs of storage technologies for ammonia, hydrogen and methane.

Energy carrier	Process power consumption MW_{el}*	Production Capacity kg/h	Investment costs €/kW**	Maintenance and Operating costs €/kW	Capital costs of storage capacity €/kg
Ammonia	1.23	100	450	16	25 [53]
Hydrogen	5,9 [54]	100	300-850 [55]	21-42 [56, 57]	600-900 [55]
Methane	20.8-27.6 [58]	100	400-2500 [55]	16-100 [55]	8/127 [59]

*Power consumption was calculated on base of the 100 kg/hr production.
**kW refers to power consumption

The prices for ammonia and hydrogen storage, transport and production cost can vary per country by currency and energy price (Table 8).

Table 8. Production, transport and storage costs for ammonia and hydrogen [51].

	Hydrogen (€/kg H_2)	Ammonia (€/kg H_2)
Production	2.70	3.40
Pipeline transport	1.69	0.17
Storage		
1 day	0.71	0.03
15 day	1.78	0.05
182 day	13.48	0.49

The production cost of green ammonia is €0.7/kg H_2 equivalent higher than that of hydrogen, assuming that the price of the bidden electricity is zero. Higher production costs are expected since the first step of ammonia production is hydrogen generation, followed by the Haber Bosch synthesis. The transport and storage costs of ammonia are however significantly lower than that for hydrogen (- €1,5/ kg H_2 equivalent). The difference in cost between hydrogen and ammonia is even more evident when the three expenses are combined (Figure 16). The storage cost of hydrogen is significant higher when it is stored for a longer period.

In all cases an ammonia-based process-chain is currently more economical than hydrogen [51].

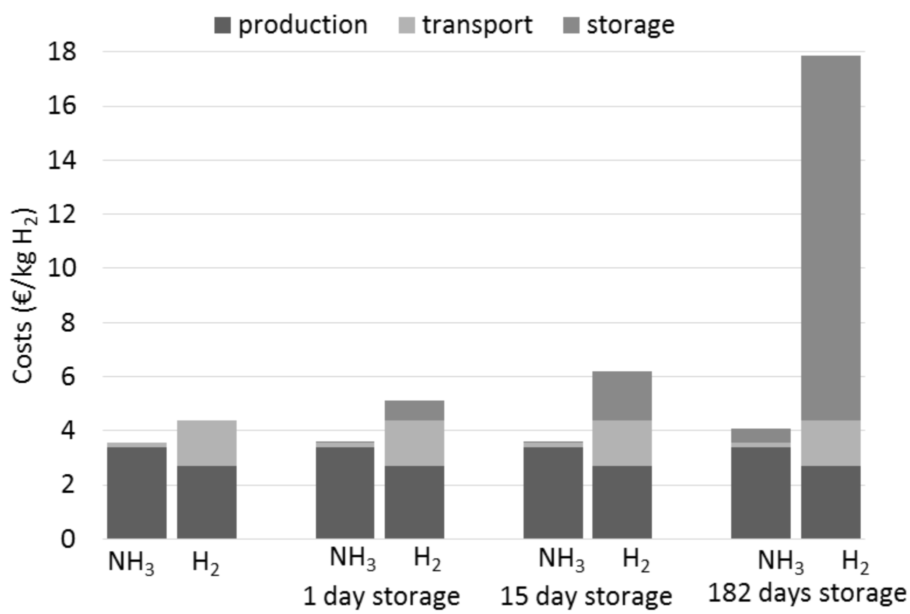


Figure 16. Total costs for ammonia and hydrogen – production, transport and storage for 1, 15 and 182 days; ammonia values normalized to hydrogen [51].

3.2. CO_2 emission reduction

Table 9 shows a worldwide ammonia production overview. It can be seen that in most parts of the world ammonia is produced using hydrogen from natural gas. China and India are the exceptions where oil and coal play an important role.

Table 9. Percentage of different fossil fuels used for production of ammonia and the energy efficiency of ammonia production in different parts of the world [54].

	Gas	Oil	Coal	GJ/t NH_3
Western Europe	100 %			35.0
North America	100 %			37.9
Russia and Central Europe	98.9 %	1.1 %		40.7
China and India	26.5 %	18.7 %	54.7 %	47.6
Rest of the world	100 %			36.4
World average	70.7 %	8.2 %	21 %	41.5

The greenhouse gas emissions from producing ammonia are shown in the Table 10. It can be seen that the average current European ammonia production (middle value from Western Europe, Centrale Europe and Russia) has 1.82 ton CO_2 equivalent for every ton NH_3 produced [11]. From the worldwide survey it is calculated that a global average emission is 3.45 ton CO_2/t NH_3 [12, 13].

With green ammonia production, environmental impact is relatively minor. According to the Intergovernmental Panel on Climate Change (IPCC), wind turbines have an emission of 10 – 20 g CO_2 eq/kWh, depending on whether offshore or onshore turbines are being assessed [60, 61]. Assuming that 179 kg hydrogen is needed to produce 1 ton NH_3, a wind-powered power-to-ammonia unit would have an emission of 0.1 – 0.2 ton CO_2 eq/t NH_3. However, it should be mentioned, that no information could be found on the CO_2 emission of the nitrogen capture process.

Table 10. Greenhouse gas emissions of the current ammonia production technology [11].

Region	**ton CO_2 eq/t NH_3**
Western Europe	2.34
North America	2.55
Russia and Centrale Europe	3.31
China and India	5.21
Rest of the world	2.45
World average	3.45

4. The possible roles of ammonia in the global energy economy

The global industrial production of ammonia is more than 170 million tons per year. Ammonia is considered to be the second-largest industrial chemical and it is used for various applications with a primary use for fertilizer production. Figure 17 shows the global ammonia consumption in the last 15 years. It can be seen that a slight decline by ammonia consumption for the industrial purposes was present in 2008 and 2009 during the economic crisis. On the other hand, the agricultural and technical demand for urea (converted ammonia) has increased.

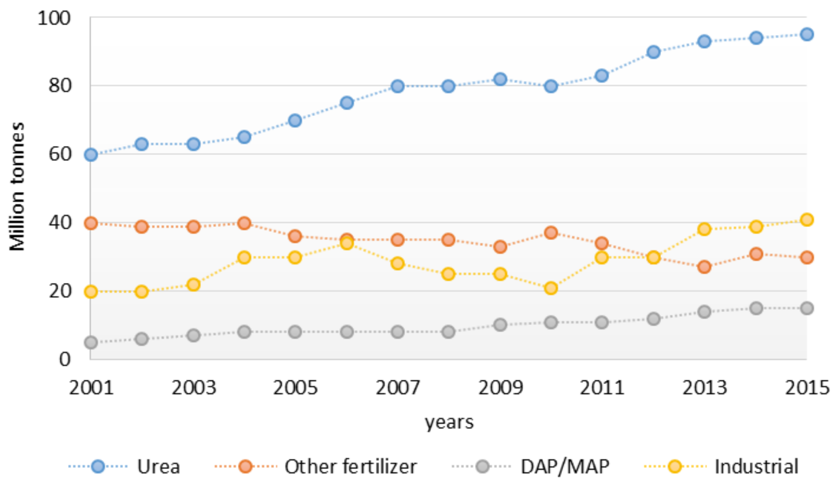


Figure 17. Global ammonia consumption as urea, other fertilizers, di-ammonium /mono-ammonium phosphate and industrial purposes.

Ammonia demand grows on average by 2 % per year. China is the biggest producer of the ammonia with 32 % of global ammonia production in 2012. Other producers are India with 9 %, United States and Russia with 7 % (Figure 18). The largest importer is United States with 35-40 % of world trade, while Europa accounts for 25 % of the trade. The areas and countries with the low costs for natural gas and limited domestic consumption are the major exporters (Latin America, Middle East and North Africa).

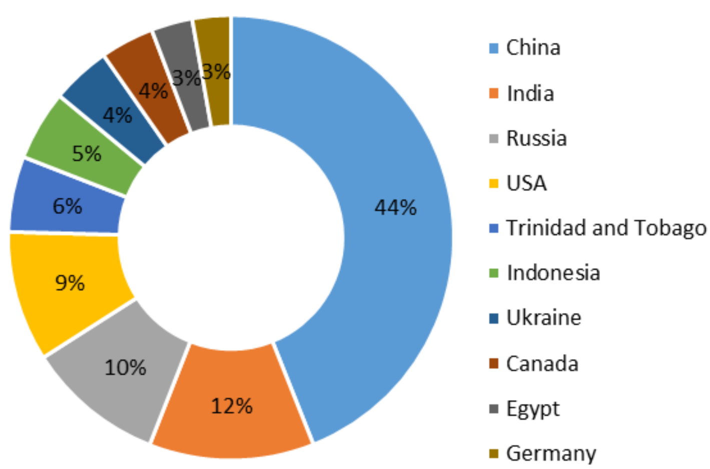


Figure 18. A schematic summary of the global ammonia producers.

In Europe ammonia is mostly produced from natural gas. The total capacity for the industrial ammonia was around 21 million tons (15 % of global production). 17 European countries produce ammonia within 42 production plants (Table 11).

Table 11. Ammonia production in Europe (2013).

Countries	Production k tons	Number of plants	% European production
Germany	3438	5	17
Poland	3210	5	16
Netherlands	2717	2	13
Romania	2176	6	11
France	1495	4	7
Lithuania	1118	1	5
Bulgaria	1118	3	5
United Kingdom	1100	3	5
Belgium	1020	2	5
Spain	609	3	3
Italy	600	1	3
Austria	485	1	2
Slovakia	429	1	2
Hungary	383	2	2
Czech Republic	350	1	2
Estonia	200	1	1
Greece	165	1	1
Total	20613	42	100

Furthermore the possible roles that ammonia as an energy carrier may play in the future of the global energy economy are discussed. The following options for usage could be identified and divided into seven most important applications:

- Energy storage, transport and usage [40, 62] - Ammonia production for storing renewable energy sources, with special attention to those characterized by uncertainties and intermittence, for their improved valorization. Ammonia can be converted into useful energy either directly, i.e. in a spark ignition engine or an electrochemical fuel cell, or indirectly via its dissociation into hydrogen. Hydrogen storage and transportation, ammonia contains more hydrogen than liquefied hydrogen itself and it is easily stored.
- Fertilizers [63, 64] - Production of liquid fertilizer solutions which consist of ammonia, urea, ammonium nitrate and aqua ammonia. Over 80 % of NH_3 production is used for fertilizer. It can be directly applied to soil as a plant nutrient or converted into a variety of common N fertilizers such as ammonium nitrate, ammonium sulfate or urea.
- Pharmaceuticals and chemicals [65] - A source of protein (ammonia together with urea) in livestock feeds for ruminating animals such as cattle, sheep and goats. Ammonia can also be used as a pre-harvest cotton defoliant, an anti-fungal agent on certain fruits and as preservative for the storage of high-moisture corn. Ammonia is used in the manufacture of nitric acid; certain alkalis such as soda ash; dyes; pharmaceuticals such as sulfa drugs, vitamins and cosmetics; synthetic textile fibers such as nylon, rayon and acrylics; and for the manufacture of certain plastics such as phenolic and polyurethanes. The food and beverage industry uses ammonia as a source of nitrogen needed for yeast and microorganisms. Ammonia is used as the developing agent in photochemical processes such as white printing, blue printing and in the diazo duplication process. Weak ammonia solutions are widely used as commercial and household cleaners and detergents.
- Mining, Metallurgy [66] - Dissociated ammonia is used in metal treating operations like nitriding, carbonitriding, bright annealing, furnace brazing, sintering, sodium hydride descaling, atomic hydrogen welding and other applications where protective atmospheres are required. Ammonia is used in the mining industry for extraction of metals such as copper, nickel and molybdenum from their ores.
- Industry [40, 41] - Ammonia is used in neutralizing the acid constituents of crude oil and for protection of equipment from corrosion. In the pulp and paper industry, it is used for

pulping wood and as casein dispersant in the coating of paper. Ammonia is used in the rubber industry for the stabilization of natural and synthetic latex to prevent premature coagulation. Ammonia is used by the leather industry as a curing agent, as a slime and mold preventative in tanning liquors and as a protective agent for leathers and furs in storage. Ammonia is used in stack emission control systems to neutralize sulfur oxides from combustion of sulfur-containing fuels, as a method of NOx control in both catalytic and non-catalytic applications and to enhance the efficiency of electrostatic precipitators for particulate control.

- Water treatment [67] - Ammonia is used in several areas of water and wastewater treatment, such as pH control, in solution form to regenerate weak anion exchange resins, in conjunction with chlorine to produce potable water and as an oxygen scavenger in boiler water treatment.
- Refrigeration [68, 69] - Ammonia is a widely used refrigerant in industrial refrigeration systems found in the food, beverage, petro-chemical and cold storage industries.
- DeNOX - Ammonia is used in various forms for using as DENOX agent in SNCR and SCR catalyst systems all around the world. This application where ammonia is used as chemical to clean the emissions in power plants or boiler operations is growing fast.

4.1. Ammonia as a source of hydrogen

One of the goals of the automotive industry is the development of low emission engine technology for vehicles to reduce their environmental impact. Among the various solutions considered hydrogen appears to be a promising alternative for automotive applications [70, 71]. The main problems with hydrogen, however, are the safe handling, storage and transport. The use of hydrogen as a fuel for wide-spread distribution in either gaseous or liquid form poses numerous safety, technical, and economical problems. One approach to resolve the drawbacks of hydrogen as a fuel includes the consideration of less expensive, simpler, and cheaper alternatives that can act as hydrogen carrier. 1 mol of ammonia contains 1.5 mol of hydrogen, which is 17.8 % by weight or 108 kg eq H_2/m^3 embedded in liquid ammonia at 20 C [34, 72].

Comparing this to advanced hydrogen storage systems, e.g. metal hydrides, which store H_2 up to 25 kg/m^3, the advantage of ammonia in carrying hydrogen per unit volume is significant [72]. Moreover, decomposition of ammonia is by definition carbon free. Thus using ammonia as a hydrogen source is a potential alternative to the conventional hydrocarbon reforming and makes the on-board hydrogen production free of carbon. There are several ways to obtain hydrogen from ammonia and it's products.

4.1.1. Catalytic decomposition of ammonia into nitrogen and hydrogen

Ammonia is unstable at high temperature and begins to decompose at 220 °C. A conversion of 98-99 % from ammonia to hydrogen is possible at temperatures as low as 445 °C. The chosen catalyst greatly influences the rate of conversion. These catalysts are mostly iron based containing Ni, Pt, Ru, Ir, Pd, Rh; alloys such as Ni/Pt, Ni/Ru, Pd/Pt/Ru/La; and alloys of Fe with other metal oxides including Ce, Al, Si, Sr, and Zr, WC, Ni/Al_2O_3, NiCeO_2 /Al_2O_3, Cr_2O_3, Ru/ZrO_2, and Ru on carbon nano-fibres. The highest conversion for catalytic decomposition is obtained on the Nano-sized Ni/Santa Barbara Amorphous (SBA)-15 and Ir/SiO_2 catalysts with conversions of 99.2 % and 98 %, respectively [73].

4.1.2. Electrolysis/Electro-oxidation of Ammonia into Nitrogen and Hydrogen

Ammonia can be electrochemically decomposed in an alkaline medium:

$$2NH_3 + 6OH^- \rightarrow N_2 + 6H_2O + 6e^- \quad E_0\text{=-0.77 V/SHE}$$

$$6H_2O + 6e^- \rightarrow 3H_2 + 6OH^-, \quad \text{E0 = -0.82 V/SHE.}$$

The thermodynamic potential for ammonia electrolysis in alkaline media is -0.77 V compared to -1.223 V for the electrolysis of water. The theoretical thermodynamic energy consumption is 1.55 Wh/g of H_2 from electrolysis of NH_3 compared to 33 Wh/g of H_2 from H_2O [73].

4.1.3. Hydrogen production from ammonia product - ammonia borane

Reaction of diborane with ammonia mainly gives the diammoniate salt $[H_2B(NH_3)_2]^+(BH_4)^-$. Ammonia borane is the main product when an adduct of borane is employed in place of di-borane [74]. Ammonia-Borane (AB) complex has a high hydrogen content (about 19.6 % wt) with a system-level H_2 energy storage density of about 2.74 kWh/L. Various catalysts can be used for this process: noble metals-based catalysts and non-noble metal-based catalysts such as Fe, Ni and Co. [73]. Ammonia borane will undergo hydrolysis in order to obtain hydrogen at room temperature in basic water, presented in the equation below:

$$NH_3BH_3 + 2H_2O \rightarrow NH_4^+ + BO_2^- + 3H_2$$

4.2. Direct ammonia-based fuel cells

4.2.1. Ammonia-based PEM fuel cells

Polymer electrolyte membrane (PEM) fuel cells cannot be used directly with ammonia. Ammonia acts as a poison to the Nafion membrane in the cells, since both the conductivity of the membrane and the activity of the catalysts are adversely affected by trace amounts of ammonia in the fuel feed. Therefore, ammonia must be decomposed externally at higher temperatures, and then the produced hydrogen can be supplied to the fuel cell. The internal ammonia decomposition is not thermodynamically favorable. If there is not 100% conversion of ammonia to hydrogen, then there could be trace amounts of ammonia in the hydrogen feed. [73].

4.2.2. Ammonia-based alkaline fuel cells

Alkaline fuel cells can be used for decomposing the anhydrous ammonia, aqueous alkaline electrolytes are tolerant to ammonia. [73].

4.2.3. Direct ammonia solid oxide fuel cells

Few studies have investigated solid oxide fuel cells (SOFCs) for direct ammonia oxidation [75, 76, 77]. Ammonia decomposes readily at the high temperatures of SOFCs and has not been shown to act as a poison to the ceramic electrolytes utilized in SOFCs [73].

4.2.4. Ammonia vehicles

As previously mentioned ammonia can be used as a fuel and converted into energy either by using an internal combustion engine (ICE) or electrochemical fuel cell by decomposing into hydrogen [78].

Oil shortages, CO_2 emissions and the cost of fossil fuels constitute the main problems of the traditional combustion engine, while electric cars do not currently have the flexibility to be a viable option for everyone. The ammonia-based car is designed to meet these challenges. The first vehicle that travelled using ammonia was designed in Belgium in 1943 (Figure 19 a)).

a) b)

Figure 19. a) The first ammonia vehicle in Belgium in 1943 (Vercruysse and Rug) and b) an ammonia vehicle today.

The Greg Vezina, The AmVeh, Marangoni Toyota GT86 ECO explorer (Figure 19 b)) and Kia Morning G/L bi-fuel are experimental ammonia cars currently being developed. Ammonia is directly injected and burned into an ICE. The Greg Vezina's ammonia car uses a dual fueled diesel and ammonia engine [79]. First the diesel is used to start the engine and to initiate the ignition of ammonia after the car is started. The AmVeh (ammonia vehicle) is an ammonia fueled car from South Korea that uses 30 % gasoline and 70 % ammonia. Gasoline is necessary for starting the ignition. 70 % of the carbon dioxide emission is avoided. This car can drive 10 km/L at a speed of 60-80 km/h. [80].

The Marangoni Toyota GT86 ECO explorer is also a dual fueled car. It holds up to 30 L ammonia and can travel up to 180 km CO_2 free [81]. The Kia Morning G/L bi-fuel is fuelled by ammonia and gasoline dual fuel with a ratio of 70:30. Ammonia is taken along with the fresh air from the intake manifold and a small quantity of diesel fuel is injected inside the cylinder to have the ammonia air mixture ignited. [82].

It is expected that based on the present R&D efforts by the various automotive suppliers, still big improvement could be made in the motor management to realise better efficiencies. However, first the demonstration of ammonia in vehicles shall be commonly accepted. The acceptance of ammonia in cars is however not yet at the attention of decision makers for policies and shall need man years of exploration and acceptation before further breakthrough in car development will be done for running cars on ammonia (or as Proton Ventures registered tradename :NFUEL ®).

In addition to personal transportation, ammonia can be used as a fuel for the agro-industry. HEC has produced the first dual fueled hydrogen/ammonia tractor. The tractor has no direct CO_2 emissions [83].

Ammonia has also been used as a fuel in the aircraft industry: The X-15 rocket plane was fueled by ammonia in the 1960s [84].

5. Power-to-ammonia scenarios

In order to further investigate the viability of the power-to-ammonia concept, three scenarios were developed.

Scenario 1:

Dedicated wind-powered system

This scenario considers a setup wherein an ammonia plant is placed alongside a 1.5 MW wind turbine, which acts as the sole source of electricity. The premise of this scenario is to demonstrate the viability and potential annual production hours of an ammonia plant which is powered entirely by the fluctuating energy production of a wind turbine.

Scenario 2:

Local scale power-to-ammonia system

The second scenario details a hypothetical rural region consisting of 10 houses, each with 5 kW of solar PV panels and a 150 kW wind turbine installed. The premise of this scenario is that the local electricity grid is limited to 22 kW (a realistic case if there is no mid-voltage grid in the immediate area), which will limit the export of renewable energy during peak production hours. During these times, surplus electricity will be used to power a small ammonia plant. Power-to-ammonia offers the stabilization of a power-overshooting situation and helps to avoid a local scale blackout.

Scenario 3:

National scenario

The third scenario considers how surplus electricity could be handled on a national scale. Currently, surplus electricity can be exported, stored or discarded. Assuming that energy export is not an option, it is preferable to store surplus electricity, in this case in the form of ammonia, rather than discard it. Using various future energy scenarios, the production of electricity is estimated for the entire Netherlands for each hour of the year. When production exceeds demand, the surplus electricity is (partially) used to power an ammonia plant.

5.1. Method of the renewable energy production calculations

In order to evaluate the scenarios, it is important to estimate the production of renewable energy throughout the year. Using some approximations and calculations based on historical KNMI (Koninklijk Nederlands Meteorologisch Instituut) weather data and Tennet electricity consumption data, it is possible to estimate potential net renewable energy production.

5.1.1. Wind Production

Using KNMI data and wind turbine power curves, we can estimate wind energy production for a given location with a given installed wind capacity for each hour of the year. The following equation was used for this estimate:

$$MW_{Wind} = Capacity \times Utilization \times Power\ Factor$$

The variables used in this calculation were:

- Capacity – The installed wind capacity; depending on the scenario, this ranges from 1.5 to 25,000 MW.
- Utilization – The maximum peak output which is assumed to be achievable at any given time (due to maintenance, connectivity issues, etc.), typically set at 82 %. This number may be 100 % when modeling a single turbine.
- Power Factor – The amount of energy produced according to the current wind speed, as a percentage of total capacity. We use the power curve of a Vestas 2 MW wind turbine as a basis.

5.1.2. Solar Production

The same approach was used for the estimation of the solar energy production for a given location with a given installed solar capacity for each hour of the year. The following equation was used for this estimate:

$$MW_{PV} = \frac{Capacity\ \times Utilization\ \times Hourly\ Multiplier\ \times Solar\ Irradiance}{1000}$$

The variables used in this calculation were:

- Installed Capacity (MW) – The amount of installed solar energy capacity; in the case of the national scenario (Scenario 3), this is assumed to be equal to 10 % of installed wind capacity.
- Maximum PV utilization – The maximum peak output which is assumed to be achievable at any given time (due to variation in PV panel orientation, tilt angle, efficiency, etc.), set to 75 % in our scenarios.
- Solar Irradiance (W/m^2) – The measured solar irradiance for each weather station.
- Hourly Multiplier – A multiplication factor used to correct for the South-West facing, 45˚ tilt angle typical of solar panels compared with the KNMI measurement on a horizontal plane.

5.2. Assessment of green ammonia production – the dedicated wind-powered system – Scenario 1

The main assumption in this scenario is that an ammonia plant is constructed alongside a 1.5 MW wind turbine. It is also assumed that there is no electrical grid connection available and the electrolyzer can be powered exclusively by the wind turbine. Surplus energy from the wind turbine is simply discarded. The aim of this scenario is to demonstrate the viability of the construction of an ammonia plant which is powered solely by renewable energy, assuming that the electrolyzer can be quickly turned on or off depending on the availability of energy.

For the assessment of the wind resource in the Netherlands, the database from KNMI for 2014 at the locations of Hoek van Holland, Eelde and Eindhoven was used.

For the calculations an electrolytic hydrogen-production energy-cost of 4.5 kWh/m^3 was taken. The ammonia production for the system consisting of an 1.5 MW nominal wind turbine and an electrolyzer with the same nominal power was used. Figures 20, 21 and 22 show the generation profiles of a 1.5 MW wind turbines which will be further used for the production of ammonia with renewable hydrogen, via the Haber- Bosch process. There are seasonal peaks visible for the generation profile. During the winter months the wind tends to be stronger.

The wind turbines at Hoek van Holland, Eelde and Eindhoven generated 7.41; 2.92 and 2.15 GWh/year power.

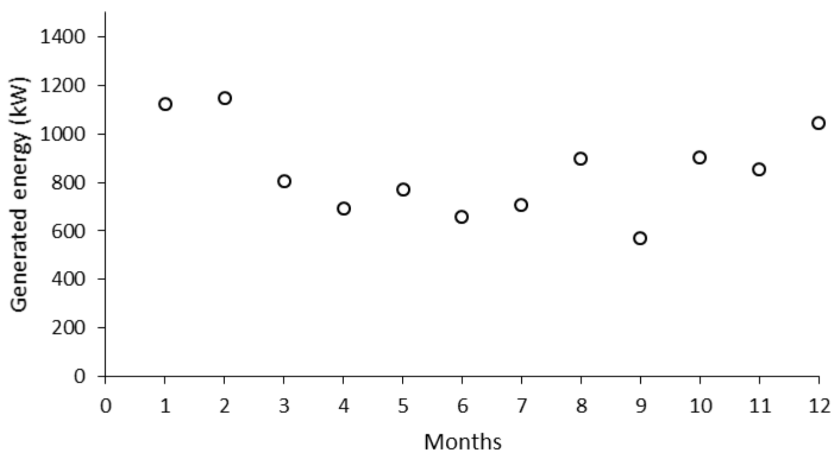


Figure 20. Generation profile of 1.5 MW nameplate wind turbine at Hoek van Holland for 2014 (monthly average values).

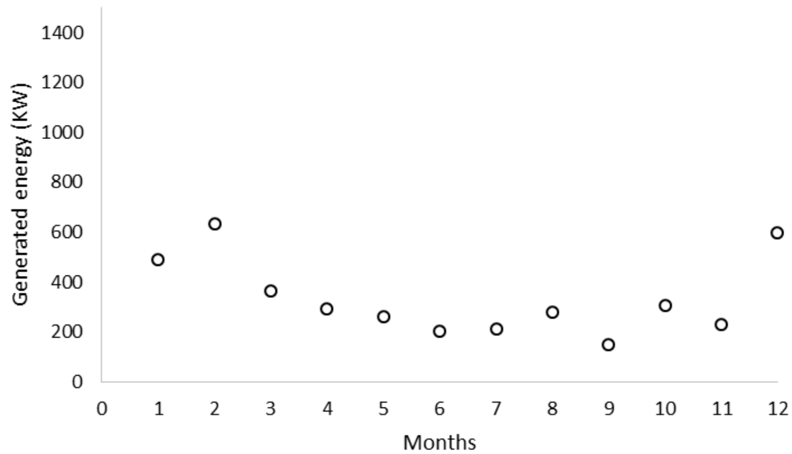


Figure 21. Generation profile of 1.5 MW nameplate wind turbine for 2014 at the location of Eelde (monthly average values).

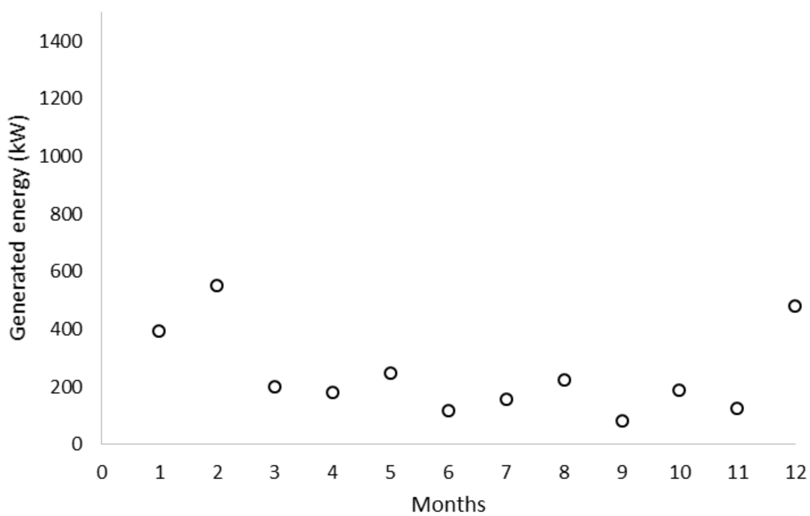


Figure 22. Generation profile of 1.5 MW nameplate wind turbine for 2014 at the location of Eindhoven (monthly average values).

For any given ammonia plant size, the flows of reactants and products throughout the plant can be easily calculated. The flow rates through the system are determined from the stoichiometry of ammonia. Ammonia is 82.25 % nitrogen by mass; and 17.75 % hydrogen by mass. Table 12 shows the total ammonia production for these three places, as well as their nitrogen and hydrogen consumption. For the calculations an energy requirement of 10 400 kWh per ton of NH_3 produced was assumed.

Table 12. Total ammonia production for Hoek van Holland, Eelde and Eindhoven according to their electricity generation profile.

Place	Total ammonia produced tons/year	Nitrogen consumption kg per day	Hydrogen consumption kg per day
Hoek van Holland	712	1603.8	343.7
Eelde	281	631.3	135.3
Eindhoven	207	465.5	99.8

From the comparative research conducted in the chapter 2.3.1., it can be concluded that the electrolyzer type suited for the produced amount of energy in this case scenario would be the alkaline electrolyzer. In this situation alkaline electrolyzer would be more convenient than PEM since it is more cost effective and has long term stability compared to PEM. However, ammonia production has specific technical requirements that must be met to achieve successful operation, high pressure and temperature. Additionally, some of the requirements originate from the fragile nature of the catalyst: pressure and temperature cycling degrade the effectiveness, as do oxygen, sulfur and other elements. Other considerations are the result of economic factors: a continuous process enables more ammonia to be produced than a batch process, and in less time. As a result, ammonia plants are designed to run using pure reactants, at nearly constant pressure and temperature, almost continuously for their entire lifetime. A continuous operation can be challenging with a fluctuating renewable energy source.

5.2.1. Short-time storage of ammonia for a local scale power-to-ammonia plant

The suitable storage methods for the estimated amount of ammonia production from a 1.5 $MW_{nominal}$ wind turbine would be pressurized vessels and portable tanks. Pressurized vessels and portable tanks for ammonia storage are available in a number of convenient sizes. Table 13 presents the possibilities for the ammonia storage.

Table 13. Suggested storage of ammonia according to a 100 kg/hr of ammonia production.

Amount of ammonia kg/h	Pressurized vessel Steel H II					ISO container			Total price of the storage units €
	Number of units	m^3	Length m	Diameter m	Sheet thickness mm	Number of units	Capacity L	Dimensions m	
100.14	1	6	2.04	1.8	14.7-18.7	1	16630	0.51x0.20x0.22	48 000
100.14	0	6	2.04	1.8	14.7-18.7	2	16630	0.51x0.20x0.22	72 000

The data were calculated and were made on two possible cases. First of having one pressurized vessel (Steel H II) for using as a storage buffer and one ISO tank that would be loaded for the further transport of ammonia at the end of the day. A second possibility could arise from using two ISO tanks with the storage duration of 5 days. Ammonia could be further unloaded and stored in the larger tanks (OCI tanks) until it can be pumped into the various means of transport for delivery to the customer or directly transported to the user.

5.2.2. A simple technical evaluation of Scenario 1

The viability of an ammonia plant is defined by the hours per year the plant is running, and by the amount of surplus energy which the plant utilizes. These factors are defined as:

1. Capacity Factor: Defined as the ratio between an ammonia plant's average working capacity and its maximum working capacity. For example, an ammonia plant with a nominal power of 1 MW which consumes an average of 500 kW would have a capacity factor of 50 %.
2. Surplus Energy Utilization: Defined as the percentage of surplus energy which the electrolyzer and the ammonia plant are able to consume. For example, if we have an

average surplus power of 1 MW and an ammonia plant is able to consume 750 kW of this energy on average, the surplus energy utilization would be 75 %.

In general, the higher an ammonia plant's rated power, the lower the capacity factor, but the higher the surplus energy utilization.

Based on the electricity production pattern, the capacity factor and the surplus energy utilization for an electrolyzer/ammonia plant of a given size can be estimated. The power of the electrolyzer determines the maximum hydrogen production rate that is achievable and directly influences the size of the ammonia synthesis unit.

In this scenario, the capacity factor is strictly defined by the availability of wind energy. Since ammonia production (coupled with a nitrogen buffer) can be easily ramped up and down, we assume that the ammonia plant consumes all available energy up to its rated capacity, with surplus energy being discarded.

Figure 23 shows the capacity factor and wind energy utilization of a theoretical electrolyzer/ammonia plant with a variable rated power in Eelde in 2014.

An electrolyzer/ammonia plant with a rated power of 400 kW would have a capacity factor of approximately 50 % (i.e. on average, the facility is consuming 200 kW) and would utilize approximately 60 % of available wind energy (with the remainder being discarded).

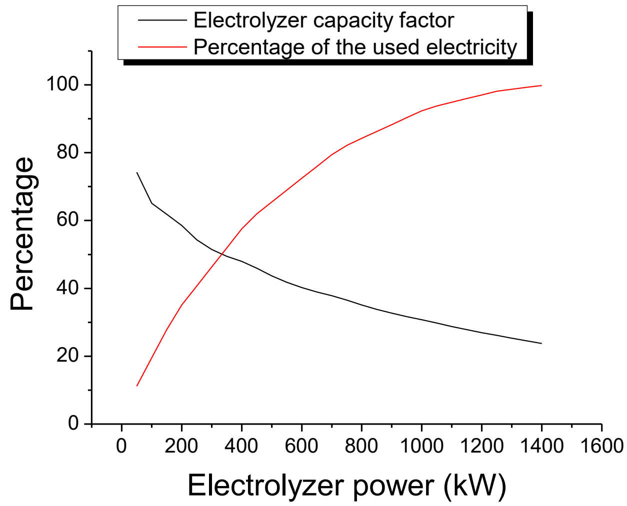


Figure 23. Electrolyzer capacity factor and surplus energy utilization within Scenario 1 for a theoretical ammonia plant in Eelde in 2014.

This same analysis was also performed for a theoretical ammonia plant at Hoek van Holland, as shown below (Figure 24).

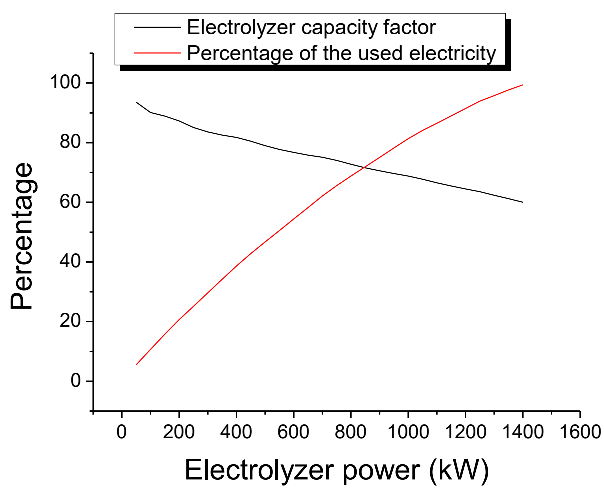


Figure 24. Electrolyzer capacity factor and surplus energy utilization within Scenario 1 for a theoretical ammonia plant in Hoek van Holland in 2014.

Since Hoek van Holland is more consistently windy than Eelde, we expect a greater availability of wind energy. As a result, we see a relative increase in the electrolyzer/ammonia plant's capacity factor, but a decrease in the wind energy utilization for a given plant power. In short, more wind energy means an ammonia plant will run more often, however, a significant amount of energy is also discarded.

Eindhoven is a relatively non-windy location. Hence, the theoretical capacity factor of the ammonia plant is relatively low, while the available wind energy utilization is relatively high (Figure 25).

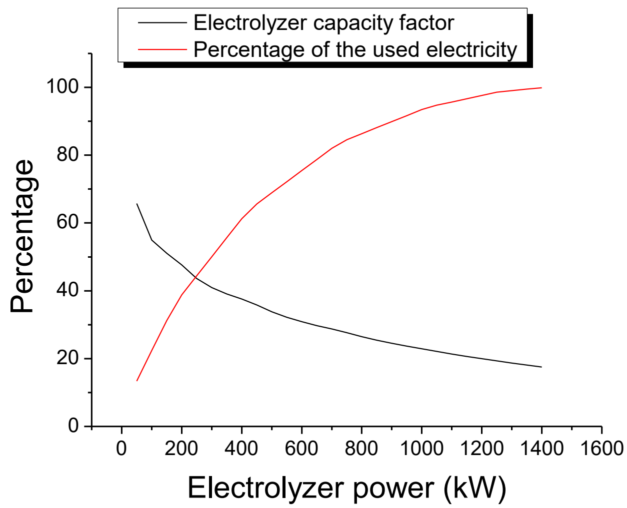


Figure 25. Electrolyzer capacity factor and surplus energy utilization within Scenario 1 for a theoretical ammonia plant in Eindhoven in 2014.

Based on the rated power of the ammonia plant and the available wind energy, we can conclude that the capacity factor and wind energy utilization may vary greatly. Notably, these relations are not linear, so appropriate sizing for an ammonia plant will be location-dependent.

5.3. Green ammonia production in the countryside – Scenario 2

The second scenario describes a rural region with ten households. Each household is assumed to have 5 kW of solar panels and a 150 kW wind turbine installed. Additionally, there is a poor grid connection (i.e. there is no mid-voltage grid in the immediate area), which will limit the potential grid capacity to 22 kW. 22 kW was adopted because of a fact that one house will consume on average 440 W, but as much as 5 kW, though not all the houses have a peak consumption simultaneously (when the electrical connection of the households was designed, the grid capacity was based on the average consumption of the households: 0.44 kW per house times 10 houses times safety factor of 5). This limitation reduced the amount of renewable energy which can be exported at a given time. In this scenario, surplus energy (i.e. energy which is not consumed directly or cannot be exported due to grid limitations) was used to power a hypothetical ammonia plant. Similarly to the first scenario, the ammonia plant's capacity factor was defined by the availability of surplus energy.

5.3.1. Excess Energy Production

As described in chapter 4.2, solar and wind energy production for each hour of the year at a given location were estimated. From this value a rough modeled electricity consumption pattern for the ten households in our scenario was subtracted. Furthermore, it is assumed that of the remaining electricity which is produced, as much as possible (in this case, up to 22 kW) was exported through the electricity grid. Any remaining 'surplus' electricity was either discarded or used to power an ammonia plant. Figure 26 displays the theoretical 'surplus' energy for each hour of the year in Eelde, Hoek van Holland and Eindhoven after accounting for self-consumption and energy export.

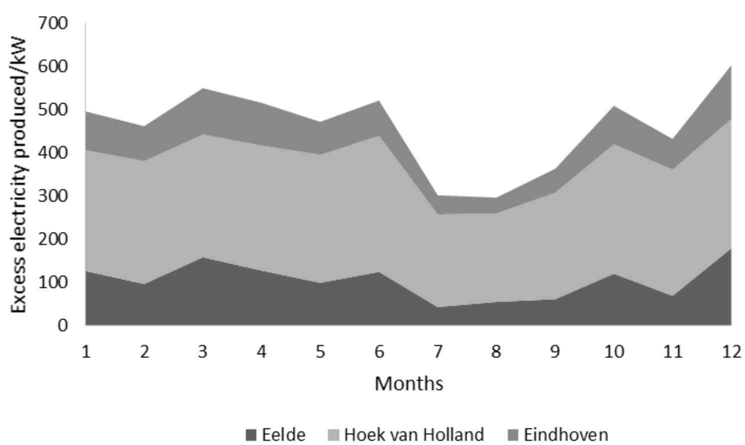


Figure 26. Theoretical surplus energy production for Scenario 2 in 2013 for Eelde, Hoek van Holland and Eindhoven.

5.3.2. A simple technical evaluation of Scenario 2

As in the previous scenario, the capacity factor and surplus energy utilization of a theoretical ammonia plant at three locations within the Netherlands, Eelde, Hoek van Holland and Eindhoven, were estimated. According to our analysis, in all three locations the solar energy production was quite similar, while wind energy production varied greatly: largest in Hoek van Holland, followed by Eelde and Eindhoven. Figure 27 shows the capacity factor and surplus energy utilization for an ammonia plant with a given rated power in Eelde. In this case, an electrolyzer with a rated power of 200 kW consumed roughly 75 % of surplus renewable energy and had a capacity factor of 35 % (equivalent to the ammonia plant running 128 days per year).

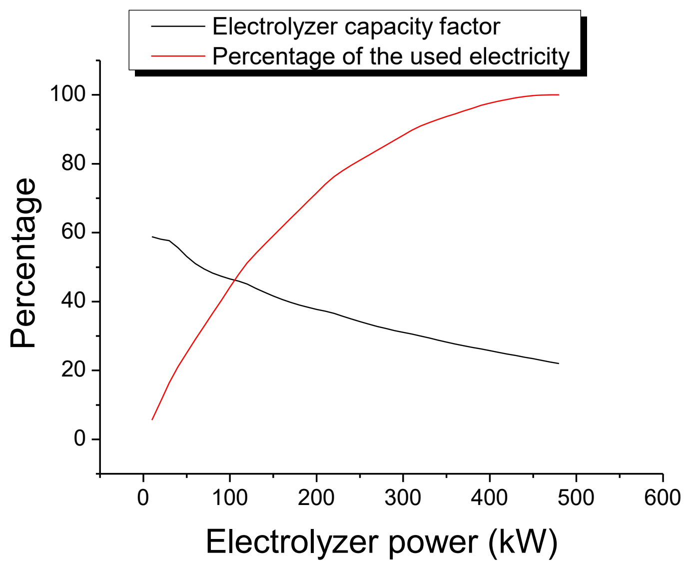


Figure 27. Electrolyzer capacity factor and surplus energy utilization within Scenario 2 of a theoretical ammonia plant in Eelde in 2014.

As a comparison, figure 28 shows an ammonia plant located in Hoek van Holland. It can be observed that as a result of the increased wind energy production, a much higher capacity factor is obtained, however a slower rise in surplus energy utilization is achieved. Following the above mentioned example, a 200 kW electrolyzer in this case would utilize approximately 55 % of surplus energy, having a capacity factor of nearly 80 % (equivalent to running 290 days of the year).

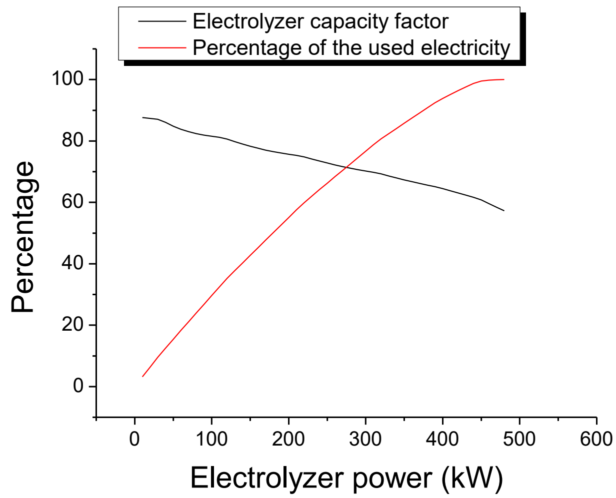


Figure 28. Capacity factor and surplus energy utilization within Scenario 2 of a theoretical ammonia plant in Hoek van Holland in 2014.

Finally, Figure 29 presents the case for Eindhoven. From the three locations that were analyzed, Eindhoven had the lowest potential renewable energy production and hence the lowest capacity factor, with a surplus energy utilization similar to that of Eelde. Furthermore, a 200 kW electrolyzer in Eindhoven would utilize roughly 80 % of surplus energy, while its capacity factor would be around 30 % (the equivalent of working 110 days of the year).

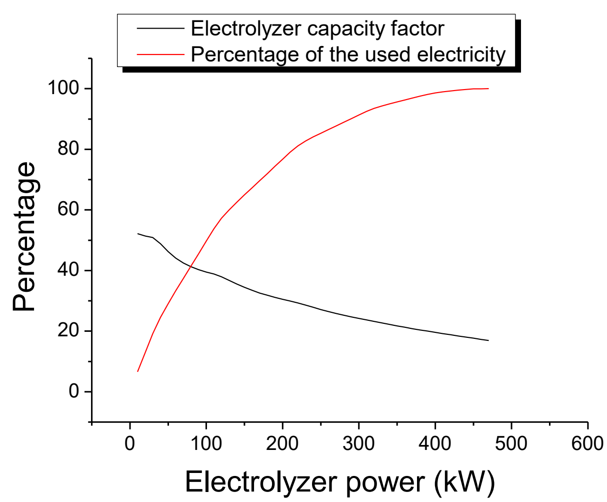


Figure 29. Capacity factor and surplus electricity utilization within Scenario 2 of a theoretical ammonia plant in Eindhoven in 2014.

In both scenario 1 and 2 a suggestion would be to combine PEM and alkaline electrolysis. The alkaline electrolysis for constant production of hydrogen and PEM can be switched on in <10 seconds (from standby) to catch surges when the electricity production peaks and the electricity demand is low. PEM is recommended when high fluctuation is present. It has a low deployment time and has a wide range of current density which provides more flexibility than alkaline. A battery could also provide cheap stored electricity when the electricity price is high.
Furthermore, these scenarios demonstrated the potential viability of ammonia production as a means of utilizing/storing surplus energy production in remote areas. It can be seen that viability was extremely location dependent and may not be feasible in all cases. However, this option could provide an alternative to simply discarding surplus energy production or investing in additional electricity grid infrastructure.

5.4. FlexNH$_3$ – Green ammonia production on a national scale – Scenario 3

As the amount of renewable energy generation within the Netherlands increases, it is likely that 'surplus' electricity will become increasingly available. 'surplus' electricity is considered to be electricity which is produced by renewable systems (e.g. wind and solar power), but cannot be immediately used. Since it can be quite expensive to store or transport surplus electricity [24], it may be beneficial to consume this energy immediately, for example, by powering an ammonia production process.
This chapter describes the methodology used to estimate the potential of ammonia production as a grid balancing mechanism on the national level: It describes the calculations, assumptions and analysis of the data.
In order to determine the potential for ammonia production as a grid balancing mechanism, it is first important to estimate how much 'surplus' renewable energy is available on a national level at any given time.

5.4.1. Renewable energy production on a national scale

It is assumed that electricity is produced by a mixture of renewable and non-renewable sources: wind, solar, coal, gas, nuclear power plants and electricity import. For solar energy, a relatively even distribution of the installed capacity throughout the country is assumed. For wind, a higher concentration of capacity in (windier) coastal areas was taken, which reflects the plans of the Dutch government to install more wind turbines in coastal provinces [3]. It is assumed that renewable have the highest priority in the electricity production list, according to the merit-order for the existing Dutch power plants [85]. Nuclear electricity cannot be easily switched on and off, therefore it has also a priority over all the other electricity sources and it was used all the time. Gas fired "must-run" combined heat and power capacity has not been considered in the calculations. The missing amount of electricity that is needed to balance the grid is assumed to be produced by non-renewable sources.

It is also assumed that the average hourly weather conditions reflect average hourly energy production. In order to estimate the amount of surplus electricity from renewable sources, TenneT's national electricity consumption data from 2011-2014 was matched with the calculated renewable electricity production. For the renewable electricity production the KNMI hourly weather pattern from the same years was used. The presence of 'surplus' energy is considered to occur when the nuclear and renewable sources alone produce more electricity that is needed on a national level. In order to estimate this, 4 different scenarios were considered:

a) Large scale scenario A: 10.000+1000 MW renewable. These numbers reflects the Dutch government's renewable energy targets of installing 10.000 MW wind turbine nominal capacity, and our assumption of 1000 MW solar installed nominal capacity. This renewable nominal capacity is conjugated with a 492 MW nuclear source.
b) Large scale scenario B: 15.000+1500 MW renewable (15000 MW wind and 1500 MW solar).
c) Large scale scenario C: 20.000+2000 MW renewable (20000 MW wind and 2000 MW solar).
d) Large scale scenario D: 25.000+2500 MW renewable (25000 MW wind and 2500 MW solar).

5.4.2. Annual Surplus Electricity Patterns

Scenario 3 considers the feasibility of an ammonia plant acting as a grid balancing mechanism on a national scale. Following this methodology, the hourly renewable energy production was estimated for each of the scenarios described above.

In the following step the 'production data' was compared to the hourly national electricity consumption data provided by Tennet. The surplus electricity production was selected to give an approximate hourly surplus electricity pattern for several years.

Using these patterns, one can try to determine an optimal electrolyzer size, depending on whether the surplus electricity consumption has higher priority (i.e. grid balancing) or electrolyzer utilization (i.e. return on investment).

5.4.3. A simple technical evaluation of Scenario 3

The results from large scale scenario A suggest that the installation of 10.000 MW wind and 1000 MW solar production capacity will not cause frequent periods of surplus energy production. Although all the results are highly dependent on the weather pattern, on average only a few hours of excess electricity production can be expected per year. Table 14 summarizes the number of excess hours obtained from the calculations.

A more frequent appearance of excess periods would follow the installation of 15.000 MW wind and 1500 MW solar capacity in large scale scenario B (see Table 15 and Figure 1). These excess periods become more prevalent in scenarios C and D, indicating an increased necessity for an adequate technology to store excess electricity.

Table 14. The number of hours per year when excess renewable electricity is produced in Scenario 3.

Number of national excess hours per year				
	2011	2012	2013	2014
Large scale scenario A	71	0	1	0
Large scale scenario B	508	463	447	455
Large scale scenario C	1801	1892	1874	1641
Large scale scenario D	3133	3236	3256	2971

The following Figures (30, 31 and 32) describe the relationship between surplus electricity consumption and electrolyzer capacity. Larger or smaller electrolyzers could be utilized with a higher or lower focus on grid balancing in mind.

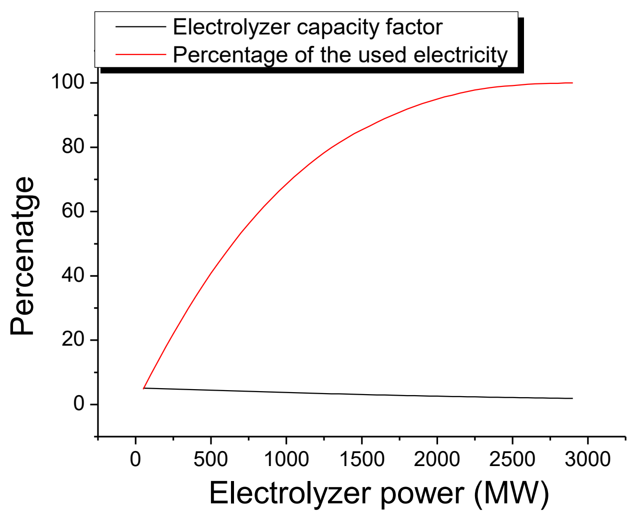


Figure 30. Correlation between surplus electricity consumption and electrolyzer capacity with 15.000 MW wind and 1500 MW solar installed capacity for 2014.

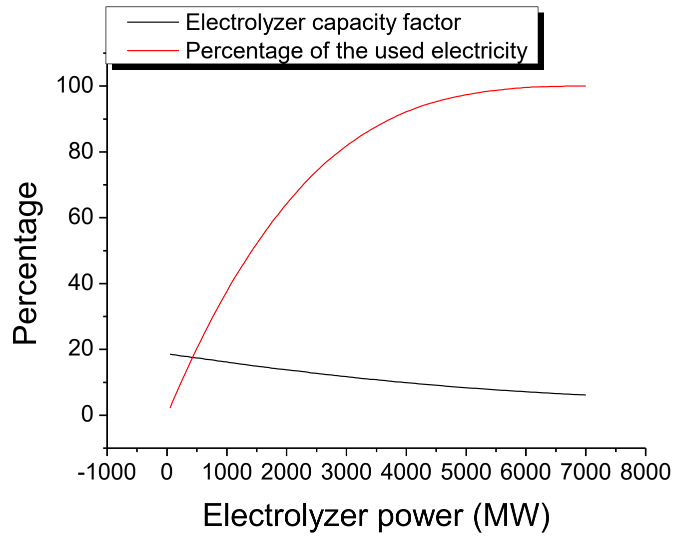


Figure 31. Correlation between surplus electricity consumption and electrolyzer capacity with 20.000 MW wind turbine capacity and 2000 MW solar panel installed for 2014.

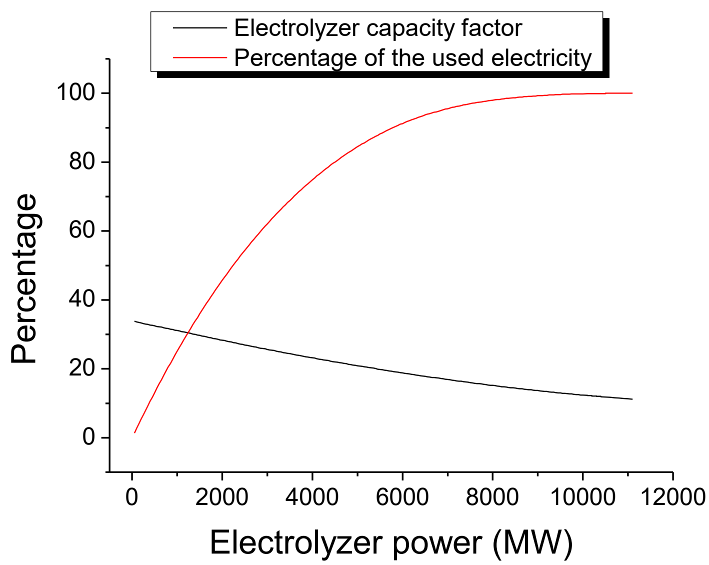


Figure 32. Correlation between surplus electricity consumption and electrolyzer capacity with 25.000 MW wind turbine capacity and 2500 MW solar panel installed for 2014.

Figure 33 shows the total ammonia production profiles (ton/year) based on the surplus electricity from the discussed renewable nominal capacities. The total ammonia production was based on the assumption that 10 400 kWh electricity is needed for the production of one ton NH_3 (4.5 kWh for producing one m^3 of H_2).

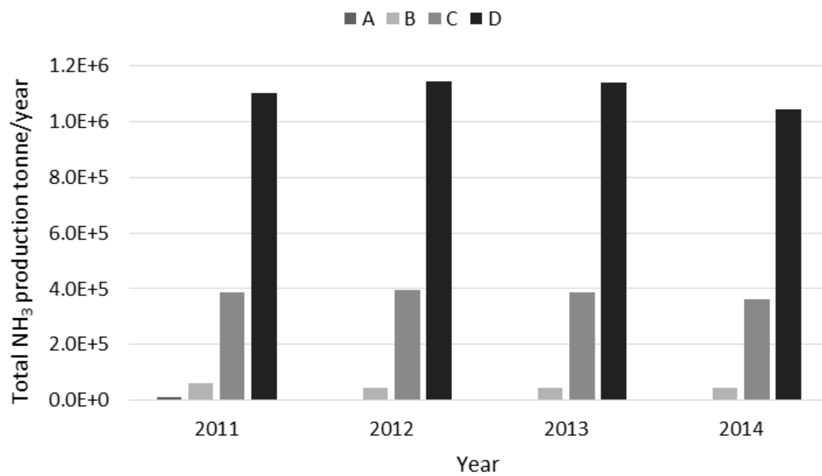


Figure 33. Total ammonia production per year according to the modeled surplus electricity for large scale scenario A, B, C and D.

From Figure 33 it is clear that a higher nominal renewable capacity produces more surplus that could potentially be used for ammonia production. Or in other words, higher nominal renewable capacity creates more energy surpluses, thus requiring more energy consumption (i.e. for ammonia production) as a grid balancing mechanism.

6. Economic feasibility of power-to-ammonia

A techno-economic analysis was performed in order to investigate the economic feasibility of the power-to-ammonia concept. MathWorks Matlab platform was used for the simulations. Two scenarios where used for the calculations, a local, smaller scale power-to-ammonia scenario, and a larger scale national scenario.

The simple technical evaluation of the two local scenarios from chapter 5 showed that the pattern of the renewable electricity production is location specific, but for a given location the correlation between the surplus electricity consumption and the electrolyzer capacity showed similar tendencies, independently of the technical boundaries of the scenarios. Therefore, the local scenario in our economic feasibility study will be a combination of Scenario 1 and Scenario 2, where the local scale green ammonia plant is assumed to have an adequate electrical connection to the electric grid.

The economic feasibility of the national scale power-to-ammonia infrastructure is discussed within the technical boundaries of Scenario 3.

6.1. Economic feasibility of the local scenario

When wind (and solar) energy is used to produce hydrogen, the highly intermittent nature of the renewable electricity does not allow a steady flow of hydrogen. However, the ammonia production unit requires a steady reagent flow. Two main methods were identified for the local scenario to achieve a steady hydrogen flow and minimize the number of reaction interruptions : i) the adaption of a hydrogen storage tank that acts as a buffer and ii) electricity import from the grid during periods with no renewable electricity generation. The economic feasibility of the local power-to-ammonia scenario is discussed for these two sub-scenarios.

Several assumptions on the main economical parameters were made:

- An average factory selling price of 400 €/tone is assumed for the produced ammonia.
- The capital cost of the onshore wind turbine is 1350 €/kW.

- The capital cost of the electrolyzer is estimated using a linear equation – it is assumed that the price changes linearly with the electrolyzer power within the studied range. The equation is obtained from the linear fit of the prices obtained from several electrolyzer sizes from different manufacturers:

$$Capital\ Cost_{electrolyzer} = 180000 \cdot Power(MW) + 910000$$

- The capital cost of the ammonia plant is estimated using a linear equation, similarly to the previous case:

$$Capital\ Cost_{NH3\ plant} = 621 \cdot Plant\ size(tonneNH3/year) + 5000000$$

  The price contains the capital cost of all the needed compressors and the nitrogen producing unit. Nitrogen is extracted locally from the air.
- The capital cost of the pressurized hydrogen storage tank is 900 €/kg H_2.
- The cost of maintenance of both the electrolyzers and the ammonia unit is assumed to be 2.5 % per year of the original capital cost.
- Both the selling and buying price of electricity are 0.08 €/kWh, unless stated otherwise.

In order to study the economic feasibility, the number of years needed to reach a break-even point was calculated for several sub-scenarios. The break-even point is reached when the cumulative income becomes equal with the cumulative costs and the business starts to make profit.

Figures 34 shows two schematic examples of the methodology to calculate the number of operational years needed for a power-to-ammonia plant to reach a break-even point. The weather profile is in both cases from 2014. In Figure 34 a) the financial balance of a 1.5 MW wind turbine-based ammonia plant installed with hydrogen storage at Hoek van Holland is presented. The line presenting the cumulative income in this scenario never intersects the line of the total cumulative costs, clearly indicating that it is not feasible to initiate a business with these parameters. Figure 34 b) presents a similar scenario with a 1.5 MW wind turbine-base ammonia plant at Hoek van Holland in 2014, but in this case without a hydrogen storage infrastructure. The continuity of the hydrogen input is achieved with the purchase of electricity from the grid in order to keep the ammonia plant running at a minimum rate. It can be seen that a business with the aforementioned technical parameters would need around 30 years to the point at which the total cost and the total revenue are equal.

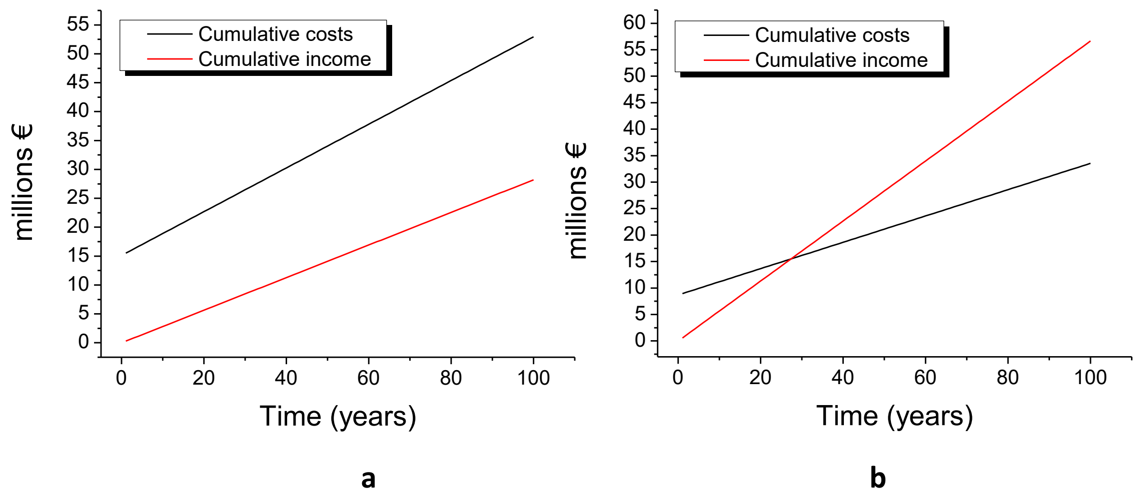


Figure 34. The variation of the cumulative costs and income as a function on years in case of a 1.5 MW wind turbine-based ammonia plant at the location of Hoek van Holland in 2014. The size of the electrolyzer is 1.4 MW. a) The continuous hydrogen supply is achieved with the help of a hydrogen storage tank buffer; b) The continuous hydrogen supply is achieved by purchasing electricity from the grid, no hydrogen storage is installed.

The capital cost of the hydrogen storage has a significant financial impact. In order to minimize this effect, the minimum size of the hydrogen storage tank needed was calculated based on the profile of the amount of hydrogen stored for a period of one year in 2014 (Figure 35). The stored amount of hydrogen is obtained from the difference between the amount of hydrogen produced and consumed. The minimum storage tank size should be able to accommodate the maximum amount of excess hydrogen present at any time, which is around 7000 kg hydrogen as per Figure 35. When the hydrogen level in the storage reaches zero, the continuous ammonia production might have to be stopped. This situation should be avoided, because any restart of the ammonia synthesis unit increases the operational expenses and decreases the lifetime of the used catalysts.

Figure 36 presents the variation of the minimum needed storage tank size as a function of the electrolyzer sizes. The minimum storage tank size changes almost linearly with the installed electrolyzer power.

The sub-scenario with hydrogen storage generally produces less ammonia than the one with purchased electricity (Figure 37).

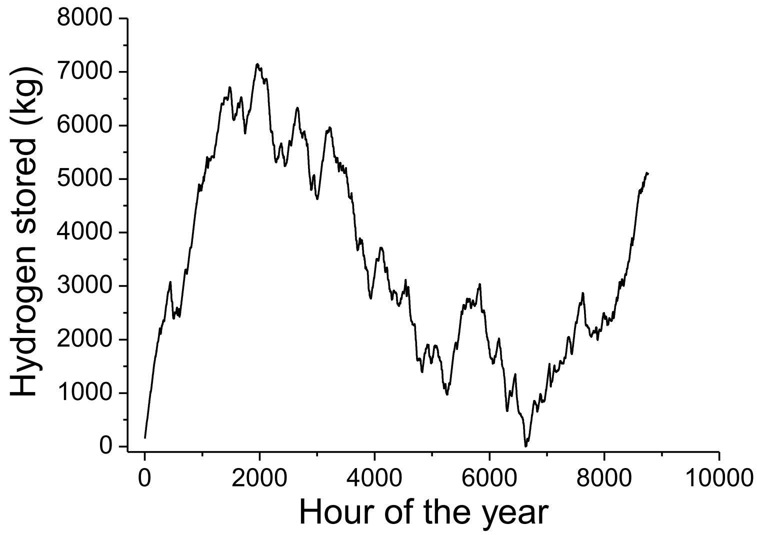


Figure 35. The variation of the amount of hydrogen stored in case of a 1.5 MW wind turbine-based ammonia plant at the location of Hoek van Holland in 2014. At the beginning of the year the storage contains 150 kg hydrogen. The size of the electrolyzer is 1.4 MW.

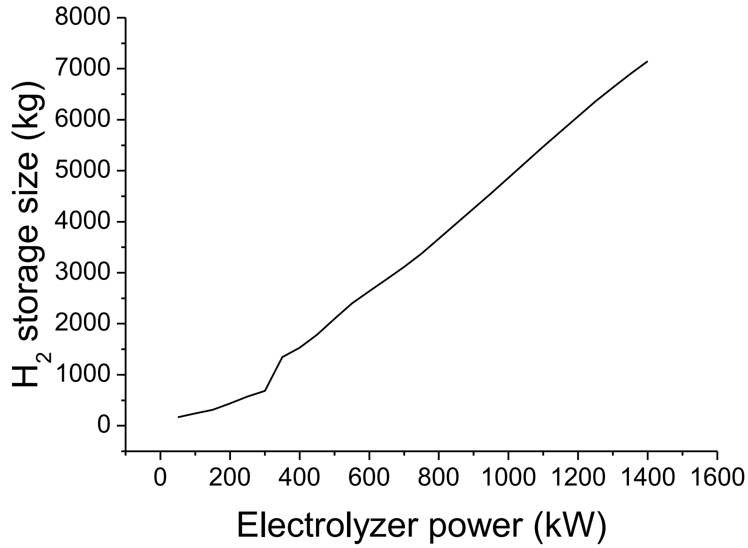


Figure 36. The variation of the minimum hydrogen storage size, that is needed to store the maximum amount of excess hydrogen present at any time, as a function of the installed electrolyzer power in case of a 1.5 MW wind turbine-based ammonia plant at the location of Hoek van Holland in 2014.

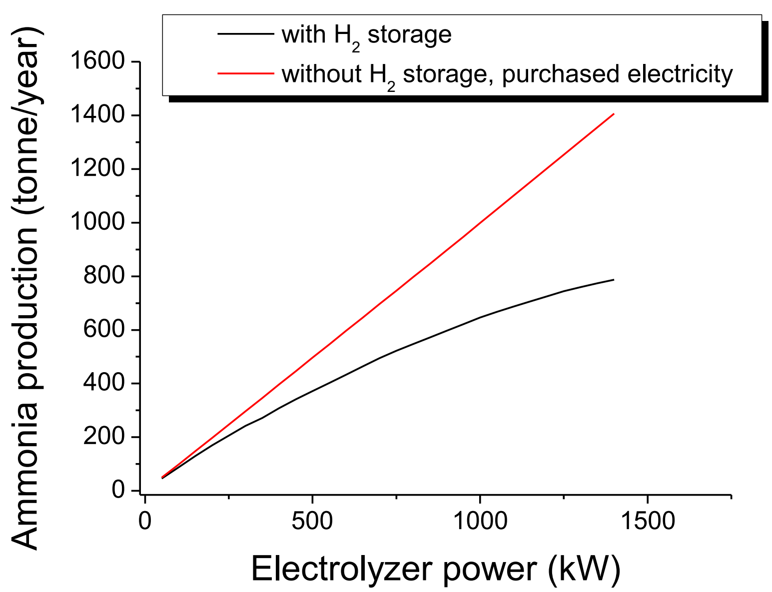
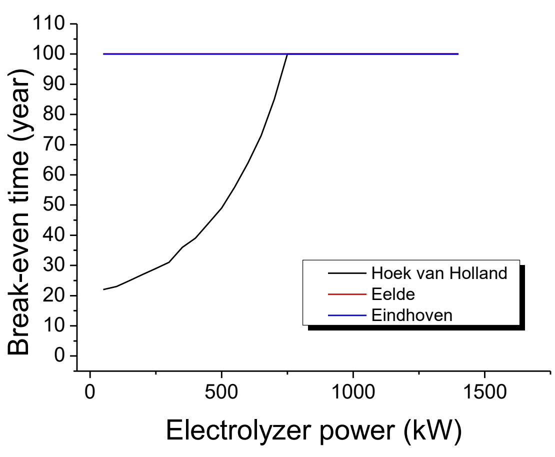


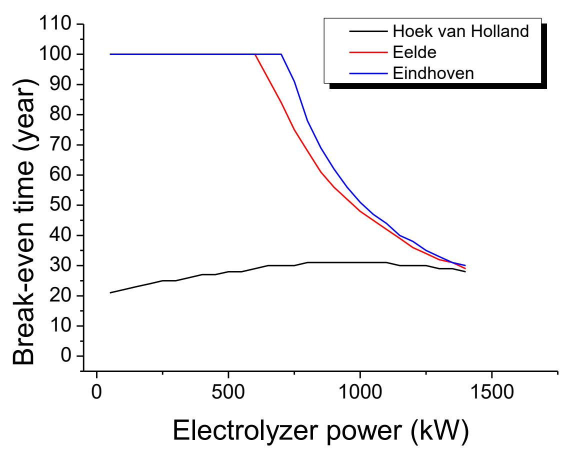
Figure 37. Annual ammonia production in case of a 1.5 MW wind turbine-based ammonia plant at Hoek van Holland in 2014 as a function of the installed electrolyzer power.

Figure 38 summarizes the number of operational years needed to reach a break-even point at various locations in the Netherlands for a 1.5 MW wind turbine-based ammonia plant. For each point on the curves, the method presented on Figure 35 was used to calculate the number of years needed to reach a break-even point. The maximum calculated time period is 100 years, therefore, if the business needs more than 100 years to reach a break-even point or if a break-even point is never achieved, the curve stays flat over 100 years.

Figure 38 a) shows that a power-to-ammonia plant at less windy locations, like Eelde or Eindhoven, would need more than 100 years to equal the total cost and the total revenue. For both locations the lines stay flat at 100 years. It is not economically feasible to initiate a power-to ammonia plant within the specified boundaries. Even the significantly windier Hoek van Holland would need at least 22 years for a break-even point with a minimum electrolyzer size, but when the electrolyzer power increases, the break-even time increases logarithmically. The increasing nature of the windy Hoek van Holland curve suggests that economically it is more advantageous to simply sell the produced electricity, instead of investing in a power-to-ammonia plant. However, that would not offer any benefits for a scenario where excess renewable electricity has to be stored.



a



b

Figure 38. The number of years needed to reach a break-even point in case of a 1.5 MW wind turbine-based ammonia plant at various locations in 2014. a) The continuous hydrogen supply is achieved with the help of a hydrogen storage tank buffer; b) The continuous hydrogen supply is achieved by purchasing electricity from the grid, no hydrogen storage is installed.

In the case of the sub-scenario where no hydrogen storage is installed and some electricity is purchased to run the ammonia plant continuously (Figure 38 b)), all three locations reach a break-even point after around 30 years at the largest electrolyzer power. The lifetime of the electrolyzer and possibly other components is not likely to be so high, so practically, this sub-scenario is also not economically feasible.

6.1.1. The effect of the electricity price

In order to increase our understanding of the relationship between the electricity price and the time needed to reach a break-even point, the economic calculations for the local scenarios were performed with various electricity prices. The main assumption of this local scenario is that the selling and buying price of electricity are equal, an assumption that might not be valid in the real world, but it is applied here in order to simplify the calculations. While within the sub-scenario of the hydrogen storage buffer, electricity is only sold at lower electrolyzer powers and never bought, within the sub-scenario without hydrogen storage, electricity is both bought and sold in function of the weather profile. In both cases electricity is never sold when the installed electrolyzer power is equal with the nominal power of the wind turbine. There all the electricity produced by the wind turbine is consumed by the electrolyzer. The effect of the electricity price on the years needed to reach break-even point is depicted on Figure 39.

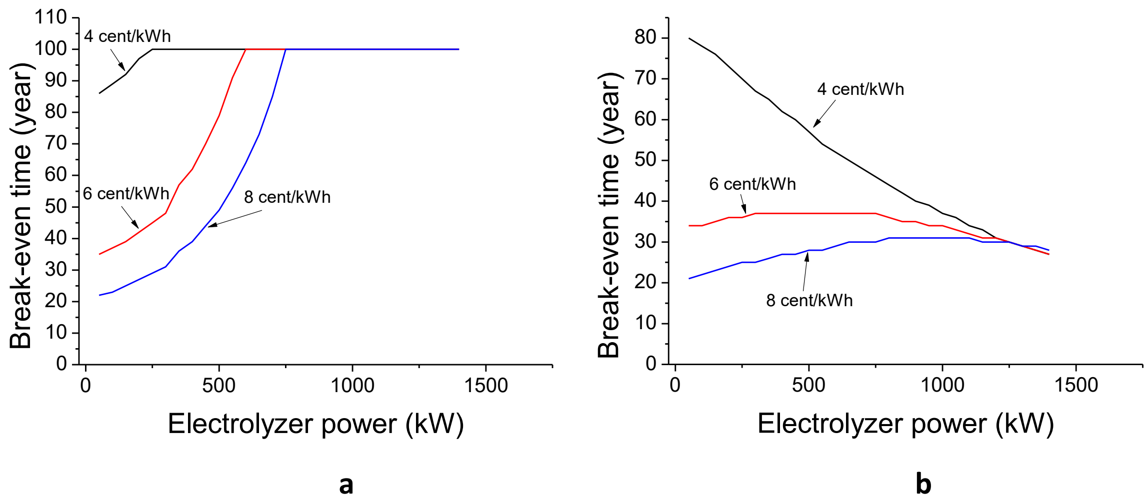


Figure 39. The effect of the electricity price on the number of years needed to reach a break-even point in case of a 1.5 MW wind turbine-based ammonia plant at Hoek van Holland in 2014. It is assumed that the selling and buying price of electricity are the same. a) The continuous hydrogen supply is achieved with the help of a hydrogen storage tank buffer; b) The continuous hydrogen supply is achieved by purchasing electricity from the grid, no hydrogen storage is installed.

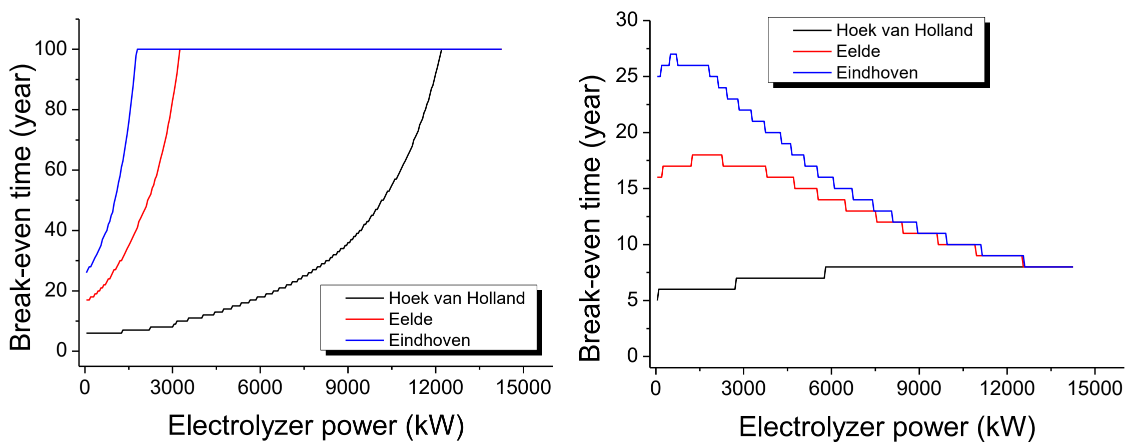
The sub-scenario with hydrogen storage it becomes less feasible with a decreasing electricity price (Figure 39 a)).

The sub-scenario without hydrogen storage is also negatively influenced by lower electricity prices. It becomes more advantageous to buy electricity, therefore the income can be maximized only at a higher electrolyzer power (Figure 39 b)).

6.1.2. Larger scale local power-to-ammonia

The influence of the size of the power-to-ammonia plant on the economic feasibility was studied by increasing the nominal wind turbine capacity and the production rate of the ammonia plant. The number of years needed to reach a break-even point was calculated for a small wind park with a nominal power of 15 MW. The same assumptions were applied for the calculations as they were presented at the beginning of chapter 6.1.

Figure 40 summarizes the results. Generally it can be noted, that the increase in the nominal power can significantly help the economic viability of a power-to-ammonia plant. In case of the hydrogen-buffer sub-scenario (Figure 39 a)) even at less windy locations the time needed for a break-even point is entering in the sub-100 year domain at lower electrolyzer powers. The increase of the electrolyzer power causes a logarithmic increase of the break-even time at all locations (Figure 40 a)).



a **b**

Figure 40. The number of years needed to reach a break-even point in case of a 15 MW wind turbine-based ammonia plant at various locations in 2014. a) The continuous hydrogen supply is achieved with the help of a hydrogen storage tank buffer; b) The continuous hydrogen supply is achieved by purchasing electricity from the grid, no hydrogen storage is installed.

For the sub-scenario without hydrogen storage (Figure 40 b)), an interesting contrast between windier and less windy locations can be noticed. The results suggest that at Hoek van Holland, a windier region, it is economically more advantageous to sell the produced electricity and avoid the investment in the power-to-ammonia infrastructure. There, the higher the electrolyzer power (and concomitantly the ammonia production unit), the higher the break-even time becomes. Still, if balancing the electrical grid and energy storage are the main priority, an investment in a power-to-ammonia plant could pay off within 10 years. At Eelde and Eindhoven, it is more advantageous to invest in higher electrolyzer powers and focus on ammonia production.

At the highest electrolyzer power, where no electricity is sold to the grid, all locations would require roughly the same number of years for a break-even point to be reached.

6.2. Economic feasibility of the national scenario

The calculations for the national scenario were performed within the boundaries of Scenario 3 presented in chapter 5.4. It is assumed, that a very large scale power-to-ammonia infrastructure is installed with one single reason, namely, the balancing of the national electrical grid. Electricity is never bought; it is just taken away from the grid to avoid any wind turbine shutdown or a catastrophic system failure that could lead to a nation-wide blackout. The only source of income in this scenario is the sold ammonia. However, the capital cost of the wind turbine infrastructure was not taken in account; it is assumed that they are already installed and are part of the system. Any financial effect on the business case of the wind turbine operators is not taken in account here.

Similarly to the local scenario, the ammonia production has to be continuous. At a large scale national level, the continuity of the ammonia synthesis can be solved only with a suitable hydrogen storage buffer.

Additionally, the following assumptions on the main economical parameters were made:

- An average factory selling price of 400 €/tone is assumed for the produced ammonia.
- The capital cost of the electrolyzer and ammonia plant is estimated using the same linear equations showed in chapter 6.1. The price contains the capital cost of all the needed compressors and the nitrogen producing unit. Nitrogen is extracted locally from the air.
- The capital cost of hydrogen storage is 30 €/kg H_2. It is assumed that an underground storage, a large cavern or area of porous rock with an impermeable caprock above it, is available.
- The cost of maintenance of both the electrolyzers and the ammonia unit is assumed to be 2.5% per year of the original capital cost.

Excess energy periods are not frequent enough in large scale scenario A and B to provide enough electricity for a successful business case. Nevertheless, for large scale scenario B with 15000 MW wind and 1500 MW solar capacity an optimal electrolyzer size can be defined (Figure 41). At an electrolyzer power of around 300 MW it would take around 30 years to reach a break-even point.

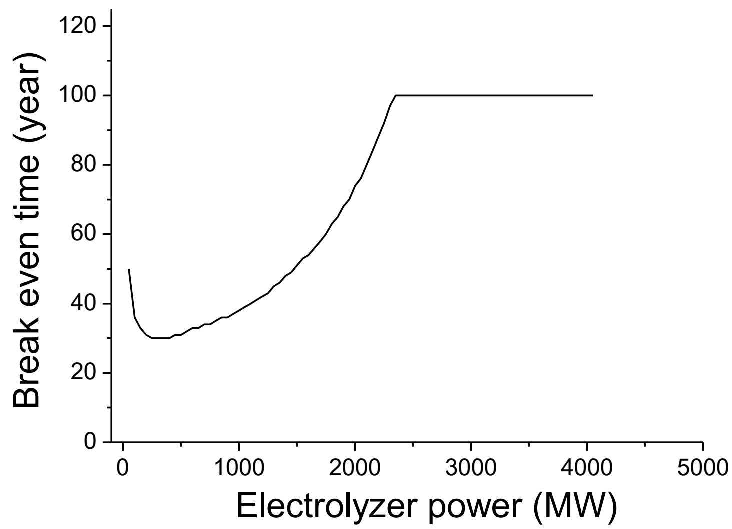


Figure 41. The number of years needed to reach a break-even point for large scale scenario B (15000 MW wind and 1500 MW solar installed capacity for 2013).

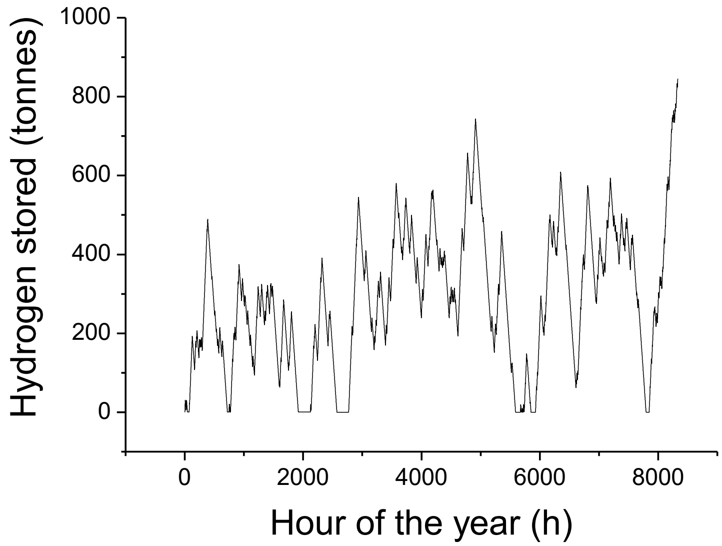


Figure 42. The variation of the amount of hydrogen stored in large scale scenario B with the weather pattern of 2013 as a function of time. At the beginning of the year the storage contains no hydrogen. The size of the electrolyzer is 300 MW.

But even at an optimal 300 MW electrolyzer power, the hydrogen storage can be nearly depleted several times per year (Figure 42), suggesting that the ammonia synthesis process may have to be stopped several times per year.

When the installed renewable nominal capacity is further increased, the economics of a national scale power-to-ammonia plant becomes more feasible. Figure 43 shows the break-even time for large scale scenario C and D. Both scenarios show an optimal plant size at lower electrolyzer power of 1000-2000 MW. At a very low electrolyzer power the amount of produced ammonia is minimal. By increasing the size of the electrolyzer and the ammonia synthesis unit, the amount of ammonia produced is also increasing, however, the increased capital cost of the infrastructure has a more significant impact on the business case.

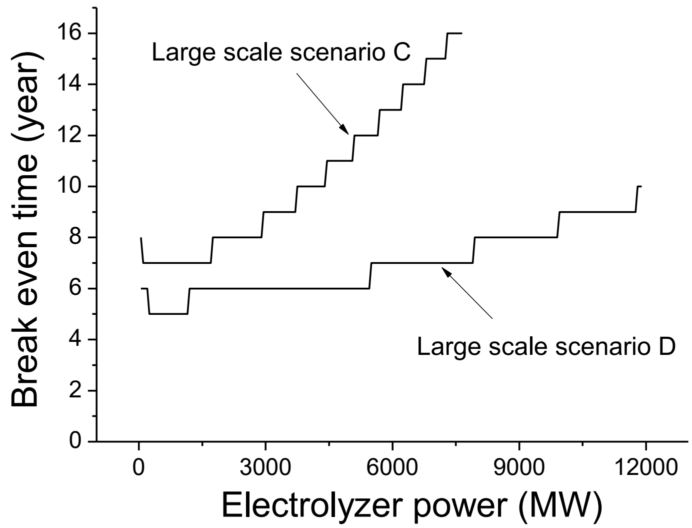


Figure 43. The number of years needed to reach a break-even point for large scale scenarios C and D (weather pattern of 2013).

7. Economical evaluation of power failures

This chapter analyses the possible economic consequences and the involved costs of a blackout. Operators in the electricity market in the Netherlands are regulated by a system of yardstick competition [86, 87]. This system was created as a substitute for genuine market incentives. Since 1976, network operators are registering power failures in their networks. The gathered information is usually used to make changes in the infrastructure of the grid.

Table 15 presents the reliability of the electrical network in the Netherlands in 2014 and the average of the preceding five years. The data is based on the individual power failure registration of the operators including the low, middle and high voltage networks [88].

Table 15. Quality indicator of the reliability of the electrical network in the Netherlands [88].

Quality indicator	2014	Average 2008-2013
Power failures	17757	19384
Affected clients per failure	125	135
Average duration of the failure (min)	72.5	80.4
Annual failure duration (min/year)	20	26.7
Frequency of power failure per year	0.276	0.332

7.1. Blackouts and social costs

The policy chief of Europe's electricity industry association was interviewed by EurActiv and revealed that Europe will have to slow down integration of renewable energies or risk power failures and system instability. "Either you go very fast in the transition – which is impossible because smart grids are expensive and the storage is not there in the needed scope – or you diminish the speed for integrating renewables into the system." A report was cited in the interview claiming the rise of serious system stability incidents in period of 2011 - 2012 from 300 to 1000 across the northern Europe. [89]

Social costs resulting from the power failure that are affecting companies and households are expressed in terms of monetary costs. This involves losses during production and waste of time. Estimated daily production losses for the companies as a result of by power failures ranges up to 120 million euros/hour [90, 91]. Even though most of the electricity is used in industry, the biggest social cost can be found in the service sector where during the day lots of added value is generated in a short period of time. The value of working hours in the service sector is 69 million euros, whereas for industry is only 10 million euros. The estimated costs of the lost time due to power failure in households in the evening period, ranges up to 85,5 million euros [91].

Table 16. Total, region specified, social costs per hour caused by power failure in millions euro, [91].

Area	During the day	Evening	Sunday during the day
Randstad	72,2	38,3	33,1
Amsterdam with surroundings	16,7	6,8	6,4
Rijnmond with surroundings	13,4	8,1	6,9
Agglomeration –s – Gravenhage	8,7	4,3	4,0
Other regions	83,8	59,3	5,5
Utrecht	13,7	6,5	48,1
Southeast-North- Brabant	6,7	4,4	3,0
Total Netherlands	156,1	97,5	81,2

From the social costs analysis that was conducted in the Netherlands, it can be seen that the highest costs are generated in larger cities (Table 16). The total cost for the Randstad region caused by a blackout during the day is estimated to be around 72 million euros per hour. The total value of one hour of undelivered electricity is 1,6 million euros and as such presents an enormous difference between social costs and unused electricity [92].

7.2. The compensation payment

Consumers and companies (with a few exceptions) are entitled to compensation if they have been affected by a power outage that lasted longer than four hours. The compensation increases gradually as the interruption lasts longer. Consumers are entitled to a statutory compensation payment as well if the damage was caused by intent or gross negligence of electricity supplier [93].

The “Compensation” is established as one of the measures to ensure the quality of the electricity networks. The scheme (Table 17) is intended as a financial incentive for network operators to invest in higher reliability, faster recovery times and troubleshooting. Values of compensation payment for low (LV), medium (MV), intermedium (IV) and high (HV) voltage connections are shown in the table 17.

Although in chapter 6 it can be seen that power-to-ammonia is not always economically feasible, it may be in the interest of society and the network operators to invest in such a system in order to avoid power outages due to renewable overproduction.

Table 17. Compensation scheme for consumers and businesses connected to low, medium, intermedium and high voltage network after a power failure [93].

Market	Failure in	Duration/ hours	Compensation	From next 4 extra hours
Consumers LV-connection ≤ 3x25A	HV-network MV-network LV-network	4 - 8	€ 35,00	€ 20,00
Small businesses LV-connection > 3x25A	HV-network MV-network LV-network	1 - 8 2 - 8 4 - 8	€ 195,00 € 195,00 € 195,00	€ 100,00 € 100,00 € 100,00
Large businesses MV-connection	HV-network MV-network	1 - 8 2 - 8	€ 910,00 € 910,00	€ 500,00 € 500,00
Large businesses IV/HV-connection	HV-network	1 - 8	€ 0,35 / kWgec	€ 0,20 / kWgec

8. Legal and social issues of power-to-ammonia

8.1. An overview of license obligations and environmental rules for wind turbines

In order to construct a wind turbine (park), the initiator must deal with a variety of laws and regulations. Depending on the wind turbine(s) size and local conditions, there are different license obligations, rules for the protection of the environment and local living conditions, and investigation duties which must be performed.

8.1.1. Environmental permits and exemptions

Regarding the spatial impact of a wind turbine (park), the wind turbine(s) must fit within the land use plan of the municipality in which the initiator intends to start building. Before that, the initiator shall submit an Environmental Permit for building (the former Building Permit) within the meaning of the Environmental Law (General Provisions) Act (Wet algemene bepalingen omgevingsrecht: Wabo) [94]. Depending on the provincial vision for wind power, the realization of solitary wind turbines may be prohibited by the province.

For the establishment and operation of a wind turbine (park), an environmental impact assessment must be performed (Milieu Effect Rapportage (MER)) which accounts for all positive and negative consequences for the environment and the local living conditions. This obligation applies at a wind farm that consists of at least three turbines and a joint capacity of 15 MW or more, or at a wind farm that consists of ten wind turbines or more. Starting from three wind turbines, limited to an output of 15 MW, the competent authority has a 'duty': the competent authority must make certain that within the local situation no MER-rating is required [95]. If the competent authority – or the initiator itself – decides that a MER must be prepared, the initiator shall submit an Environmental Permit for the establishment and operation of a device (the former Environmental Permit) [96]. These environmental permits are also referred to as an ‘All-in-one Permit for Physical Aspects’, which means that this permit comprises several individual environmental permits.

Instead of an Environmental Permit for establishment and operation, an All-in-one Permit for Physical Aspects limited environmental impact assessment (Omgevingsvergunning Beperkte Milieutoets (OBM)) may in cases be sufficient [97]. This OBM allows the competent authority to omit the need for the preparation of a MER and consists only of a permission or a refusal. If the competent authority judges that an MER must be prepared, the initiator shall submit a license for the creation of a plan. In other cases, in principle no further environmental permit is required.

8.1.2. Other permits and exemptions

In addition to the Environmental Permit, an exemption or a license may be required on the basis of the Flora and Fauna Act (Flora- en faunawet: Ffw) and the Nature Conservation Law (Natuurbeschermingswet: Nbw). Because the – intentional or unintentional – killing, injuring and troubling of protected species under the Ffw is prohibited, it is important prior to the realization of a wind farm to take into account the potential impacts on these species. An exemption on the basis of the Ffw shall be granted only if it is determined that there is no negative effect on the favorable conservation status of species [98]. Also for protected areas, such as Natura 2000 sites, the ecological area (Ecologische Hoofdstructuur: EHS) has to be examined in advance if the realization of a wind turbine (park) is deemed harmful to the protected nature. In that case a license is required [99].

Additional licenses are required on the basis of the land use plan or municipal or provincial regulation, such as demolition and/or logging permits. Having regard to the fact that a wind turbine (park) in most cases will need to be connected to the public electricity grid, it is also required to obtain a license for the building of the electricity cable. These permits and exemptions can be included in the application for an Environmental Permit (All-in-one Permit for Physical Aspects). As regards to the exemption on the basis of the Flora and Fauna Act and the license on the basis of the Nature Conservation Act, a declaration of no reservations must be asked of the competent authority.

On the basis of a special law, a permit or exemption may be needed, for example on the basis of the Ontgrondingenwet, the Soil Protection Act (Wet bodembescherming), the Water Act

(Waterwet) and the Public Works Act (Wet beheer rijkswaterstaatwerken). The application for permits and exemptions on the basis of these laws are to be submitted separately.

8.1.3. Competent authority

In principle, the college of Mayor and Aldermen of the commune decides on the application's approval [100]. Nevertheless, the Executive Council of the Province has to apply the provincial coordination scheme in the realization of wind turbines with an installed capacity between 5 and 100 MW [101]. Instead of the college of Mayor and aldermen, the Executive Council has exclusive jurisdiction to grant all licenses, exemptions and statements of no concerns may be required [102]. From an installed capacity of 100 MW or more, wind energy projects also fall under National Coordination Regulation (Rijkscoördinatieregeling). In practice, an initiator of a wind turbine (park) with an installed capacity between 5 and 100 MW goes first to the appropriate municipality.

8.1.4. General rules that apply to all wind turbines

Since the building and operation of one or more wind turbines affects the local living conditions, a set of general rules has been established relating to security and maintenance, noise, shading and light glare ("flicker") and external security. These conditions are set out since 1 January 2011 in the Activities Decree (Activiteitenbesluit milieubeheer) and the associated Regulation (Activiteitenregeling)) and they apply also if a wind farm requires an All-in-one Permit for Physical Aspects limited environmental impact assessment [103].

The maximum noise emissions of a wind turbine for example, amounts to a maximum of 47 dB L_{day} as weighted annual average and a maximum of 41 dB L_{night} for the night [104]. These emission standards must be fulfilled on the facade of noise-sensitive buildings (for example, nearby homes) or on the border of sensitive areas. To reduce flicker, a wind turbine that is within a certain distance of sensitive objects (such as nearby schools or homes) must be fitted with an automatic stop facility. If an average of more than seventeen days a year for more than twenty minutes per day flicker occurs on facades where windows are, the wind turbine should shut down automatically [105]. In the framework of external security – this includes, for example, the breakdown of the blades of a wind turbine – it is desirable to have a minimum distance between so-called (limited) vulnerable objects and wind turbines. That is why in this Activities Decree rules are also formulated for the so-called localized risk: the chance each year that a person who would reside in that place on a continuous basis unprotected dies as a direct result of an unusual occurrence within that establishment [106].

In addition, wind turbines can disturb civil and military aviation radar systems. That is why within 75 kilometers (measured from the top of the radar antenna) of radar disruption areas, a maximum height is formulated to the tip of the blades. That maximum height varies by radar monitoring of the area and is set between 89 and 136 meters [107].

In order to enable the competent authority to verify that all the rules are met, the initiator has a duty to inform the competent authority at least four weeks before the construction of the wind turbine [108].

As wind energy is combined with the production of ammonia, next to the permit for wind turbines, the consequences of the production and storage of ammonia on the local living conditions also have to be taken into consideration. The wind energy-ammonia complex must fit within the zoning plan of the involved municipality.

Without prejudice to the outcome of further investigation, the establishment of a wind energy-ammonia complex is most easily established in existing industrial areas where there is experience with both chemical activity and wind energy, as in the Rijnmond in Rotterdam [109].

8.2. License obligations of a renewable ammonia plant

Obtaining the construction permit for building an ammonia plant could run into some difficulties. When referring to the ammonia production of more than 50 tons/day and the installation of large volume storage tanks, one would need to go through the same permitting obstacles as for the large industry plants [110, 111]. Moreover, most of the time the same restrictions as for renewable energy are applied – it's placing is forbidden in touristic and natural areas and in many municipalities ammonia storage tanks are not allowed within the city limits.

An additional requirement is to gain permission for the grid connection. To define the grid connection concept, Tennet examines based on the request whether the grid conditions at the existing location or planned grid connection point are able to be connected to a plant without any problems on the already existing grid.

In order to investigate the request for the new connection point, Tennet will gather the necessary information from the connectee (form in Appendix A) [112].

Moreover, regarding the connection to the low and mid-level grid, permitting concerns for the ammonia and storage should not present a problem.

8.3. Social acceptance of power-to-ammonia

Public acceptance of ammonia, which has been discussed only in a few studies, has shown that even though in a properly running plant no or minimal leakages should occur, it is likely that communities will be against nearby ammonia plants [62]. This kind of public reaction could be caused by the associations of various issues to ammonia (unpleasant odor, accidents, perceived low safety when handling ammonia).

Two social psychological models predict citizens' intention to act in favor of against a new technology from psychological variables: (i) the Norm Activation Model, which assumes that people act based on moral considerations, and (ii) the Theory of Planned Behavior which assumes that people act out of self-interest [113]. No literature was found that applied these models on a power-to-ammonia-complex, but the main conclusions of this study on new energy systems could be also applied here.

Analyses on data collected from a group of Dutch participants who received information about hydrogen as a fuel, hydrogen technology, and the opinion of stakeholders, suggests that intention to act both in favor of against the new energy technology was more strongly based on moral considerations than on self-interest [113]. If the theory of planned behavior variables were added to a model that included norm activation model variables, the explained variance increased for the supporters group, whereas this was not the case for the opponents group. These results indicate that for supporters of hydrogen refueling facilities, self-interest is a secondary goal after moral considerations but that this is not the case for opponents. The strongest determinants of intention to act in the supporter group are personal norm, positive affect and perceived effect of the technology. In the opponents group, these are personal norm, negative affect, trust in industry, the perceived effects of the technology and distributive fairness. A number of policy recommendations could be implemented in the case of a power-to-ammonia complex as well. Policy makers should design policies based on moral considerations in citizens' behavioral intentions. This may strengthen and improve the moral benefits of the technology and the way it is implemented. This can be done by making the technology more beneficial for society and the environment, making the technology very safe for citizens, and by distributing the costs, risks and benefits as fairly as possible. Sufficient information may help to create the missing link between problem perception on the one hand and the evaluation of the technology and behavior towards the technology on the other. Studies about the acceptance of hydrogen fuel-stations suggest that resistance is particularly fueled by perceived unfairness with respect to distribution of costs, risks and benefits and low levels of trust in industry. A dialogue with the public starting in the early phases of planning may help to avoid the perception of unfair decisions and may create greater trust within the community [113].

9. Stakeholder analysis of power-to-ammonia

As energy systems evolve to meet climate targets, there will likely be many new stakeholders involved in the operation and maintenance of the electric grid. The power-to-ammonia concept has the technical maturity to play a leading role as a balancing agent and additionally provide a flexible bridge between the energy world and the chemical industry. In order to further understand the position and implementation of power-to-ammonia within the energy system, a brief overview of the identified stakeholders is presented here (Figure 43). A detailed description of the characteristics of these stakeholders and their interactions with each other and with power-to-ammonia is not part of this study, but rather would be a topic of a follow-up project. However, to gain an idea of what role power-to-ammonia could potentially play in future energy systems, the following future energy system scenario is presented.

The main stakeholders identified in the power-to-ammonia concept are:

Roles	**Responsibilities**
Active demand and supply (e.g. Power-to-ammonia)	• Own assets which can provide 'balance' to the grid • 'Balance' can be provided in the form of active energy demand and/or supply • Acts as a bridge between the energy consumer and the transmission / distribution system operator, providing a higher quality energy service
Energy / NH_3 consumer	• Consumes energy / NH_3, e.g. producing fertilizer • Negotiate and sign contract with energy suppliers.
Aggregator	• Aggregates flexibility from multiple parties (e.g. power-to-ammonia) and offers it to the program responsible party via a trade platform • Based on the trades executed they control the energy production / consumption of e.g. power-to-ammonia facilities • Offers trading platforms for trade on energy markets. • Offer a minimum guaranteed price to their customers in case their assets are deployed
Energy supplier	• Supplies and buys energy / NH_3 to and from the consumer and the aggregator (direct supply purchase agreements)

	• Actively trades with e.g. power-to-ammonia via the aggregators platform and via markets such as APX • All the trades executed on the APX market and on the trade platform operated by the aggregator have to be settled via the energy supplier
Balance responsible party (BRP)	• Active on the energy balancing market • Provides balancing services to the transmission system operator • Purchases flexibility via aggregators • Creates 'energy programs', utilizing active demand & supply, in order to create a stable energy supply • Setup and operate energy program management
Transmission system operator (TSO)	• Sets up and operates high voltage transmission system lines • Provides transportation services (approx 40.000 to 60.000 euros/MW grid capacity) grid capacity • Sets up and operates balancing markets • Verifies 'energy programs' • Requests changes in 'energy programs' if necessary
Distribution system operator	• Setup and operate distribution system lines for gas and electricity • Receive energy consumption programs from BRPs and forecast any possible congestions • Circumvent congestions by utilizing active demand / supply • Connect consumers and producers to their network • Collect metering data and make it available to the relevant energy retailers and the system operator
Producer	• Produces energy, e.g. wind farm • May be curtailed / dispatched by the TSO or the BRP
Government	• Creates and enforces the regulatory framework • Provides oversight on environmental / social acceptance of industries • Provides project permits • May provide subsidies for important energy services
Nearby inhabitants	• Provide approval for the implementation of industries • Bear the risk of technological failures • May be remunerated relative to their proximity to new projects

The potential future relationship between the different stakeholders is shown in figure 44 below. As shown, a power-to-ammonia facility would likely play the role of 'active demand and supply'. The power-to-ammonia facility would be directly connected to the distribution grid or transmission grid in order to consume excess electricity and also potentially consume ammonia to produce electricity during peak demand times. The power-to-ammonia plant would likely be controlled by an 'aggregator' – a third party which aggregates the flexibility provided by many different parties, and sells that flexibility as required, based on a merit order. In this way, the flexibility and balancing potential of a power-to-ammonia facility can be utilized by the 'balance responsible party' in order to provide stability to the grid. Any ammonia or energy produced by the power-to-ammonia facility would be sold to consumers via a supplier.

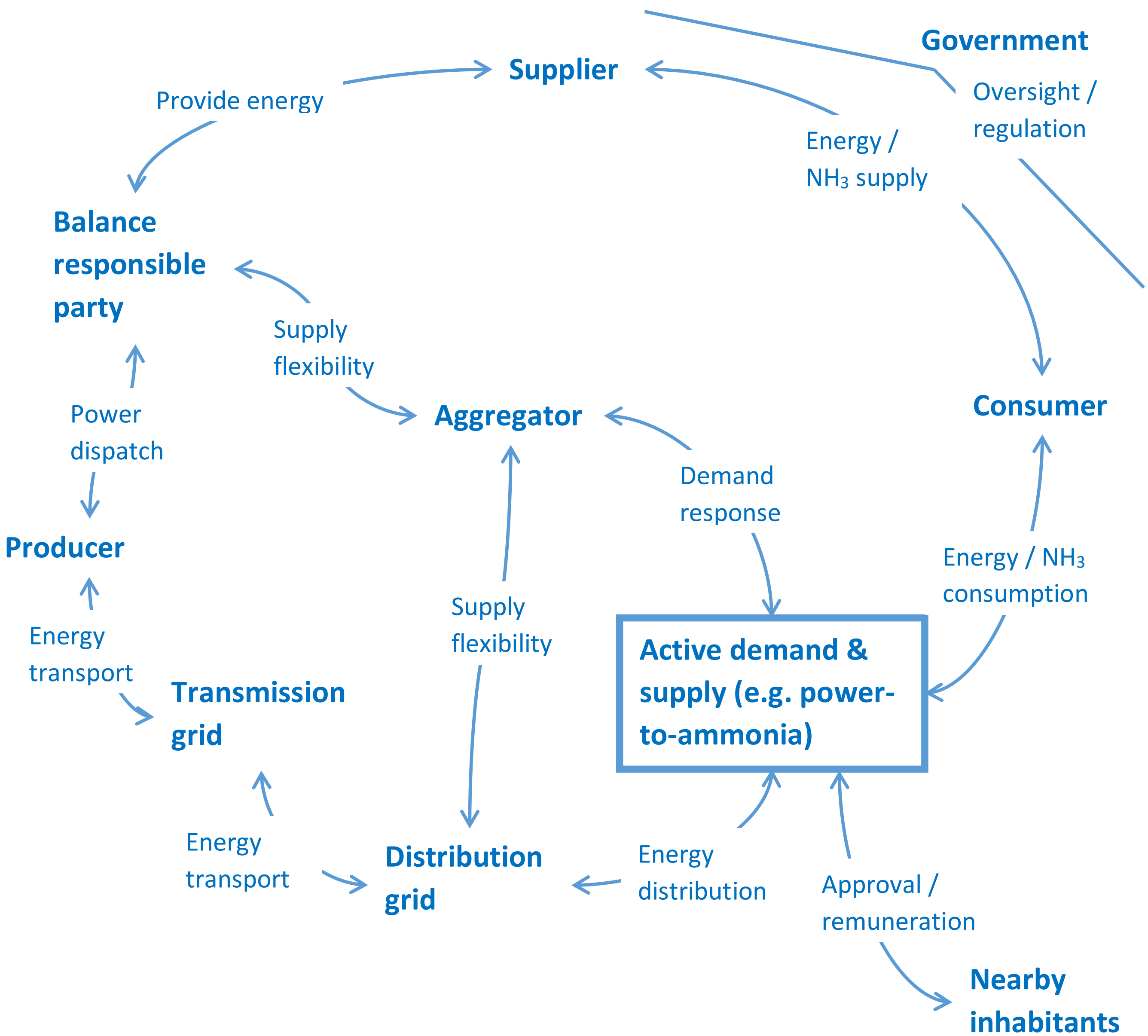


Figure 44. Future stakeholder interaction model.

All the above stakeholders would be at least tangentially active in a power-to-ammonia value chain. For successful power-to-ammonia initiatives, it is necessary that these stakeholders interact, negotiate, exchange resources and align visions. There are many operational, financial, safety, legal and administrative limitations that can block the success of a power-to-ammonia project. While stakeholders may focus on maximizing their own financial gains, we can see that all stakeholders must work closely together in order to provide a stable energy supply. A well formulated policy could enable many stakeholders to cope with future electricity grid problems by supporting the development of active energy demand and supply technologies, such as power-to-ammonia facilities.

10. Conclusions

The storage of the excess renewable electricity will become a necessity as renewable energy production increases in order to stabilize the electrical grid against unpredictable production peaks. Power-to-ammonia is a prominent alternative to store excess production in a chemical form and decrease the carbon emissions of both the energy sector and the chemical industry.

This study showed that ammonia production with renewable power is technically feasible with current technologies. Hydrogen production through water electrolysis, nitrogen separation and ammonia synthesis are all technically feasible and proven technologies. The ammonia synthesis step is a high pressure and temperature catalytic process and requires a continuous reagent flow. The highly intermittent nature of the renewable electricity sources does not allow a continuous flow of hydrogen. Therefore, two main methods were identified for the local scenario to achieve a steady hydrogen flow and minimize the number of reaction interruptions : i) the adaption of a hydrogen storage tank that acts as a buffer and ii) electricity import from the grid during periods with no renewable electricity generation.

The elimination of the costly hydrogen storage tank from the plant design and the adaption of a strategy wherein electricity is purchased to run the process at the lowest possible production rate during periods with no renewable energy production, offers an economical advantage for local scenarios. Additionally, the transport and storage costs of ammonia are significantly lower than that for hydrogen. The storage cost of hydrogen is significantly higher when it is stored for a longer period.

At windier locations it is economically more advantageous to sell directly the produced electricity. However, that would not offer any benefits for a scenario where excess renewable electricity has to be stored. In moderately windy areas, on the other hand, it is more advantageous to invest in higher electrolyzer power and focus on ammonia production.

At a local level, calculations based on the historical KNMI weather pattern data and various economic assumptions showed that a power-to-ammonia plant at a minimal scale of tens of MW

nominal power is necessary. The minimum nominal power for economic feasibility is location specific.
The frequency of the excess renewable electricity production determines the economic feasibility of power-to-ammonia on a large national-scale. It was found that power-to-ammonia at very large scale could offer a successful business case when the nominal power of the installed renewable (wind and solar) energy sources would reach around 20.000 MW on a national level.

A power-to-ammonia complex must fit within the zoning plan of the involved municipality. A power-to-ammonia plant is most easily established in existing industrial areas where there is experience with both chemical activity and wind energy.
To increase the social acceptance of power-to-ammonia, the benefits of the technology and the way it is implemented have to be taken into account. A dialogue with the public should be started in the very beginning of the planning process to create trust. The advantages and disadvantages of power-to-ammonia should be distributed as fairly as possible for a project to gain public acceptance.

The research conducted in this report has led to some useful results; however it has mostly used a theoretical approach. Further research on the power-to-ammonia concept with an experimental and testing approach at a specific location would be beneficial.

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[97] *Art. 2.1(1)(i) Environmental Law (General Provisions) Act.*

[98] *Art. 75(5) and (6) Flora and Fauna Act.*

[99] *Pursuant to art. 19d Nature Conservation Act.*

[100] *Pursuant to art. 2.4(1) Environmental Law (General Provisions) Act.*

[101] *Art. 9f(1) Electricity Act in connection with art. 3.33 Dutch Spatial Planning Act.*

[102] *Unless a administrative body of the state is competent. See art. 9f(2) Electricity Act.*

[103] *Cf. art. 1.4(3)(a) of the Activities Decree.*

[104] *Art. 3.14a Activities Decree.*

[105] *Art. 3.12 Activities Regulation.*

[106] *Cf. Art. 1(1)(o) Decree on External Safety of Establishments.*

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Appendix A – Exchange of data and communication [112]

Table 19. Load grid connection.

Project Phase	Responsible Party	Documentation/Data to be provided
Feasibility	Connectee	• Connection request • Naming a desired grid connection point • Main connection data • Single line circuit diagram confirming to standard • Approximate project schedule • Official approvals and permissions
	Tennet	• Non-binding preliminary information on power consumption • Provision of general information on the grid connection point • Min. and max. short circuit current from the Tennet grid and series impedance
Stationary (steady state) study and inspection of the plant and connection concept	Connectee	• Connection capacity, load, load development • Switchgear and transformer key data • Protection concept • Details of system interactions
	Tennet	• Definition of actual requirements on the generating plant at the grid connection
Determination of the connection concept	Connectee	• Presentation of a binding connection concept • Site plans • Other official approvals
	Tennet	• Defining the limits of ownership • Additional/special requirements • Process data list • Measurement, protection, metering • Final description of the “grid connection concept” and grid connection offer
Conditions for commissioning	Connectee	• Commissioning program and schedule • Plant documentation • Protection adjustment data • Evidence of agreed properties/requirements • Evidence that the plants behave on the grid in accordance with the grid code • Inspection protocols, certificates • Other official approvals • Successful acceptance and approval for commissioning
	Tennet	• Grid connection agreement with technical specification and system management agreement • Approval for commissioning

Table 20. Generation grid connections [112].

Project Phase	Responsible Party	Documentation/Data to be provided
Feasibility	Connectee	• Connection request, stating power station type and primary energy type and also how the plant is to be operated • Naming a desired grid connection point or geographical position of the generating plant • Main connection data • Approximate schedule, stating medium-term/ long-term development • Official approvals
	Tennet	• Non-binding preliminary information on power consumption • Provision of general information on the grid connection point • Min. and max. short circuit current from the Tennet grid and series impedance
Stationary (steady state) study and inspection of the plant and connection concept	Connectee	• Connection capacity, load and operating method, load development • Connection capacity for auxiliary load and start-up • Single line circuit diagram confirming to standard • Connection of the generating plant in the normal switching state. • Switchgear key technical data • Contribution to the short circuit current into the Tennet grid and also data on load flow and short circuit current calculation • Details of the system interactions
	Tennet	• Definition of actual requirements on the generating plant at the grid connection
Determination of the connection concept	Connectee	• Presentation of a binding connection concept • Protection concept for grid connection and generating plant • Details of the possibility of providing system services • Site plans • Other official approvals
	Tennet	• Defining the limits of ownership • Additional/special requirements • Process data list • Measurement, protection, metering • Final description of the "grid connection concept" and grid connection offer
Dynamic system studies	Connectee	• Confirmation of the design data provided for the stationary steady state study • Adjustment values and block circuit diagram of the control model

		• Dynamic equivalent circuit diagram of the generators • Dynamic equivalent circuit diagram of the motors for auxiliary road • Adjustment values for components for the automatic system and description of its behavior • Concept for auxiliary road • Other data relevant to the system
	Tennet	• Stating the requirements on control devices with regard to grid security and grid compatibility
Conditions for commissioning	Connectee	• Commissioning program and schedule • Plant documentation • Protection adjustment data • Evidence of agreed properties/requirements • Evidence that the plants behave on the grid in accordance with the grid code • Inspection protocols, certificates • Other official approvals • Successful acceptance and approval for commissioning
	Tennet	• Grid connection agreement with technical specification and system management agreement • Approval for commissioning in test operation • Following evidence on the properties and troubleshooting or improvement for permanent operation approval