

# Power to Ammonia Process Options

Input to Power to Ammonia value chains and business cases





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### Summary

The rapid expansion of Dutch renewable electricity generation (target of 37% by 2020) will have a significant impact on the existing electricity market and infrastructure. Increasing variability of an already fast moving electricity market and mismatch between supply and demand are some of the possible consequences. The power to ammonia project explores a multi-faceted solution – the production, storage and use of ammonia as an energy storage medium and the production and sale of carbon neutral ammonia. ECN's role within the project was to identify the process options for various electrolyser technologies and evaluate them in terms of energy, economy and flexibility. Moreover, knowledge acquired was used to generate an R&D roadmap outlining the focus necessary to achieve a technology readiness appropriate for deployment in the medium to long term future.

The project explored the use of four different electrolysers technologies, Proton Exchange Membrane (PEM), Battolyser, Solid Oxide Electrolytic Cell (SOEC) and Solid State Ammonia Synthesis (SSAS). Comparing these technologies is done by using key performance indicators of energy efficiency, CO<sub>2</sub> avoided, cost of ammonia and system flexibility. Further insight is provided by identifying the cost drivers if deployed in the medium and long term. The benchmark used is state of the art ammonia production from natural gas.

The energy efficiency of PEM, Battolyser and SSAS systems are all lower than the benchmark. The only exception is the SOEC, here lower energy demand is achieved through high temperature operation and effective heat recovery from the ammonia reactor. Electrochemical ammonia produced using renewable electricity is CO<sub>2</sub> free when compared to the benchmark, meaning a total of 1.8 t of CO<sub>2</sub>/t NH<sub>3</sub> is avoided. On an economic front, , cost competitive ammonia can be produced by the SOEC and battolyser systems when there is high penetration of renewable energy (63%) and high fuel price. The PEM and SSAS are unable to compete with ammonia production from natural gas in any of the scenarios considered. The cost driver for all systems in the medium term is the electrolysers and in the long term, all systems apart from the battolyser continue to be driven by investments in the electrolyser. Finally, the system flexibility, quantified as response time and load range shows that for energy storage application, it is possible to operate the systems on the day ahead market but not on the 15-minute intraday or imbalance electricity markets. It must be noted that the battolyser operating in battery mode is an exception to this. For absorbing electricity directly at renewable energy source, the SOEC and SSAS are not suitable due to a minimum turndown limitation, but all other systems can be used.

The R&D roadmap established that for PEM electrolysers, material durability must be the immediate focus. While for the battolyser and SOEC, TU Delft has identified that improvements must focus on scaling up and improving selectivity of electrolysis products, respectively.

## Table of contents

1.	Introduction				
2.	System Evaluation			7	
	2.1	Ammonia from Fossil Fuels			
	2.2	Ammonia	a from Electricity	8	
		2.2.1	Water Electrolysis	9	
		2.2.2	Ammonia Synthesis	10	
3.	Benchmarking				
	3.1	Ammonia Production Benchmark		12	
		3.1.1	Energy Efficiency	12	
		3.1.2	CO <sub>2</sub> Avoided	13	
		3.1.3	Flexibility	13	
		3.1.4	Cost of Ammonia	13	
		3.1.5	Cost Drivers	14	
	3.2	Energy St	torage Benchmark	15	
4.	Conclu	isions and	R&D Roadmap	17	
Refe	References				

### 1. Introduction

Driven by a demand to decarbonise and meet the 2020 target of 37% renewable electricity generation, more and more renewable power is being connected to the existing electricity infrastructure. Possible consequences are the increasing variability of an already fast moving electricity market and mismatch between supply and demand. Conventional measures such as grid expansion and improving the capacity of flexible power plants can only balance supply and demand up to a certain level. In the long term, new solutions that enable efficient transmission and storage of the highly fluctuating and non-controllable, renewable sources are needed.

A proposed solution is using surplus electricity to make ammonia for the purpose of electricity storage. In The Netherlands a total of 2800 kta of ammonia is produced from natural gas, the carbon dioxide produced (4900 kta) corresponds to 3% of the total carbon dioxide emission [1] [2] [3] of the Netherlands. The current, complex, multi-step process consumes a significant quantity of energy (30 GJ/ton ammonia), with a majority of this energy consumption and carbon dioxide emissions stemming from the production and clean-up of hydrogen and nitrogen. Therefore, producing hydrogen via an alternate method that is less carbon and energy intensive is advantageous. When looking to the energy density and storage requirements for ammonia, it becomes clear that the relatively high energy density (18.6 GJ/ton ammonia) and storage at moderate conditions (1 bar and -33°C) make it an attractive option for energy storage.

The consortium involving Nuon, Stedin, OCI Nitrogen, CE Delft, Proton Ventures, TU Delft, TU Twente, AkzoNobel, ECN and ISPT (co-ordinator) explored the feasibility of Power2Ammonia deployment. ECNs role within the project was to identify the process options for various electrolyser technologies and evaluate them in terms of energy, economy and flexibility (Chapter 2 & 3). Additionally, drawing upon this knowledge to generate an R&D roadmap required to achieve a technology readiness appropriate for deployment in the medium to long term future (Chapter 4).

### 2. System Evaluation

### 2.1 Ammonia from Fossil Fuels

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



Figure 1 Block Diagram of Natural Gas Based Ammonia Plant (Adapted from [4])

The SMR (Steam Methane Reforming) process is shown in Figure 1. An important observation is that most of the process is used to produce and clean up the synthesis gas (hydrogen and nitrogen) required to produce the ammonia. The synthesis of ammonia only occurs in the final block.

First, the natural gas undergoes a desulphurization process to remove any sulphur compounds. Sulphur and sulphur containing compounds are poisonous to most of the catalysts used downstream. Next, the natural gas is mixed with steam (H<sub>2</sub>O) and heated (600°C) before it enters the primary reformer. Inside the primary reformer, the gas passes inside tubes that are filled with nickel containing reforming catalysts and the natural gas reacts with steam to form a mixture of carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>) and hydrogen (H<sub>2</sub>). Only 30 to 40% of the natural gas present in the feed is reformed in the primary reformer, this is due to the limitation of chemical equilibria at the operating conditions. The reform reaction is highly endothermic (heat consuming). This process is supplied with additional heat provided by burning natural gas outside the tubes. The flue gas from this combustion forms one of the largest sources of carbon dioxide emission of an ammonia plant.

The secondary reformer is used to convert the remaining natural gas present in the primary reformer's outlet stream. The gas is mixed with process air and combusted across nickel containing secondary reformer catalysts. The air is used to supply oxygen  $(O_2)$  for combustion and the required nitrogen  $(N_2)$  for ammonia synthesis. Temperatures in the secondary reformer reach

1000°C and up to 99% of the feedstock is converted. The reforming processes produces a lot of excess heat that is used to generate steam to drive compressors and supply heat elsewhere in the process. Most of the ammonia plants have steam surplus available, which sometimes is used to generate electricity. The gas exiting the secondary reformer contains CO, CO<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>, H<sub>2</sub>O and other minor compounds (methanol, amines, formic acid, acetic acid etc.). The CO is converted to CO<sub>2</sub> and H<sub>2</sub> by the addition of H<sub>2</sub>O and the use of the water-gas shift reaction. The minor compounds are condensed along with the H<sub>2</sub>O. Next, the CO<sub>2</sub> is removed using an amine based process to strip the CO<sub>2</sub> from the process gas. The ammonia synthesis catalysts are poisoned by oxygen containing compounds, therefore, any unconverted CO and CO<sub>2</sub> must be removed. This is achieved using a methanation step, where CO and CO<sub>2</sub> are combined with some H<sub>2</sub> to form methane (CH<sub>4</sub>) and H<sub>2</sub>O. The water is then removed using a drying step.

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

### 2.2 Ammonia from Electricity

The power to ammonia concept is shown in Figure 2. Essentially, the production and clean-up of the synthesis gas (hydrogen and nitrogen) is simplified by using the electrolysis of water to supply the hydrogen and air separation to supply the nitrogen. In the past, ammonia has been produced using this approach in Norway and Zimbabwe [5], however, no such plants are currently operational.



Figure 2 Block Diagram of Power to Ammonia (electrolyser refers to either PEM, Battolyser, SOEC or SSAS)

Demineralised  $H_2O$  is fed to the electrolyser, here it is split into  $O_2$  and  $H_2$ . The gas streams exit separately with limited cross-over of one component to the other side. The cross over is well below the explosive limits [6].

The exiting  $H_2$  stream is saturated with  $H_2O$  and contains some  $O_2$ . The  $O_2$  is removed by reacting it with the  $H_2$  over a precious metal catalyst to form  $H_2O$  [7]. The gas mixture is passed over a zeolite bed that selectively adsorbs  $H_2O$ , the exiting gas stream is almost pure  $H_2$ .

The  $N_2$  is produced using an Air Separation Unit (ASU) [8]. The  $N_2$  and  $H_2$  are mixed in the required composition for the synthesis of ammonia. The pressure of the synthesis gas is increased using an

centrifugal compressor. Similar to the SMR process, the ammonia synthesis is limited by chemical equilibria, therefore a recycle stream is used to increase the conversion and a purge stream is used to prevent the build-up of any inerts.

### 2.2.1 Water Electrolysis

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

$$H_2 O \rightarrow H_2 + \frac{1}{2}O_2$$
 Equation 1

#### Low Temperature Electrolyser

Low temperature electrolysers that are currently available at commercial scales are the Proton Exchange Membrane (PEM) electrolyser and Alkaline electrolyser. Another technology that falls into the category of low temperature electrolyser is the battolyser [9]. This is a dual function device that can operate as a normal battery when charging and discharging, when fully charged, the device can start performing the electrolysis of water. Only the PEM electrolyser and battolyser are explored within this project.

A PEM electrolyser uses a solid sulfonated polystyrene as an electrolyte [10]. Commonly, Nafoin<sup>®</sup> is used as the membrane. The use of a solid electrolyte allows for compact design and operation at higher pressures. The half reactions occurring in a PEM cell and the arrangement of cathode, anode and membrane are shown in Figure 3. The role of the membrane is to keep hydrogen and oxygen separate while facilitating the transport of protons. It can be noted that water is only consumed on the anode side of electrolyser, however, water is actually circulated on both sides for heat management purposes. A schematic of the PEM electrolyser is shown in Figure 3.





Figure 3. Schematic of a PEM Electrolyser (Adapted from [10]).

Figure 4. Schematic of a battolyser (Adapted from [9]).

The battolyser shown in Figure 4 uses an alkaline KOH electrolyte to conduct the OH<sup>-</sup> ions and a polymeric diaphragm is used to separate the hydrogen and oxygen while permitting the flow of OH<sup>-</sup> ions. The electrodes are constructed from nickel and iron and when operating in battery mode, have similar characteristics to Edison battery. The performance of electrolysis is similar to that of an alkaline electrolyser. Once again water is circulated on both sides of the electrolyser for heat management purposes.

### High Temperature Electrolyser

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





The schematic of the SOEC is shown in Figure 5. The hydrogen of the SOEC is 100% pure since the electrode material only allows oxygen ions to be conducted and therefore no cross over of hydrogen occurs. Often, a sweep gas is used on the oxygen side for temperature control purposes, however, this may not be required if operated at the thermo-neutral point. It can also be seen that some hydrogen is supplied to the cathode side of the SOEC. This is to aid electrode material stability.

### 2.2.2 Ammonia Synthesis

The chemical synthesis of ammonia is briefly described in section 2.1. However, in addition to this, there are also direct electrochemical synthesis methods. There are two main types of direct ammonia synthesis that is currently being researched, Solid State Ammonia Synthesis (SSAS) and the use of aqueous electrolytes [11]. There are currently no commercially available direct synthesis systems SSAS is explored within the current project.

### **Electrochemical Synthesis**

The SSAS concept is to produce ammonia directly from a source of hydrogen (water) and nitrogen (air). The production of *gaseous* ammonia has been achieved using SSAS at high and low temperatures with varying levels of success. The highest reported formation of ammonia are 1.13 x  $10^{-8}$  mol s<sup>-1</sup> cm<sup>-2</sup> at 80°C and 9.5 x  $10^{-9}$  mol s<sup>-1</sup> cm<sup>-2</sup> at 500°C [11]. However, research has identified that the commercially viable production rate is around 4.3 x  $10^{-7}$  mol s<sup>-1</sup> cm<sup>-2</sup> or above. So the current research results are still 1 to 2 orders of magnitude too low.

SSAS can be divided based on the type of electrolyte cell used; either a proton ( $H^+$ ) conducting or oxygen ion ( $O^{2-}$ ) conducting electrolyte. The use of a high temperature (850°C)  $O^{2-}$  conducting

electrolyte has been explored further within this project. A schematic of this is shown in Figure 6. All SSAS systems currently co-produce ammonia and hydrogen, the half reactions are shown in Figure 6. It has been assumed that the hydrogen and ammonia are co-produced in a mole ratio of 3:1





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

## 3. Benchmarking

Benchmarking is done to evaluate two applications of power to ammonia. First, for the production of ammonia as a chemical commodity, the different electrochemical technologies (PEM, battolyser, SOEC and SSAS) are compared with each other and with the conventional process using steam reforming of methane (SMR). Second, for the application of power to ammonia as an energy storage method, the different electrochemical technologies are compared to energy storage in other forms.

### 3.1 Ammonia Production Benchmark

The Key Performance Indicators (KPIs) used for comparison are: Energy Efficiency,  $CO_2$  Avoided, Flexibility and Production Costs of Ammonia.

### 3.1.1 Energy Efficiency

Energy efficiency is calculated by considering the all forms of energy consumed to produce a kg of ammonia. The results are expressed in specific energy demand in Table 1

System type	Specific energy demand		
	[kWh/kg NH₃]		
SMR (Benchmark)	8.6		
PEM	9.5		
Battolyser	8.9		
SOEC	7.1		
LT SSAS	8.1		
HT SSAS	11		

Table 1. Specific Energy Demand of Ammonia Production.

The highest efficiency (or lowest specific energy demand) of the SOEC is attributed to its high temperature operation which enables higher electrical efficiency. The poor efficiency of HT SSAS is due to additional heat required, which must be supplied by burning some of the produced ammonia or other alternative fuels. The impact due to the addition of heat requirement is higher for HT SSAS than for SOEC because some of the ammonia is produced in the electrolyser, this leads to a smaller Haber-Bosch reactor where less heat can be recovered.

A heat integration study of the PEM, battolyser and LT SSAS systems showed that it is possible to operate without heat input. Only cooling water and small amounts of cryogenic duties are required. It is also possible to integrate the system in such a way that heat (low or intermediate pressure steam) can be generated from the ammonia synthesis reactors. The study of the SOEC and HT SSAS shows that additional heat input is required for both systems. The SOEC requires the equivalent of 4.0% of the electrolyser power to be supplied as heat, whilst the HT SSAS requires the equivalent of 10.7% of the electrolyser power to be supplied as heat.

### 3.1.2 CO<sub>2</sub> Avoided

 $CO_2$  avoided is 1.8 ton per ton ammonia if electrochemical ammonia is produced since all of the energy demand is provided exclusively by electricity. This corresponds to 100%  $CO_2$  avoided with respect to the benchmark. However, it must be noted that this is only valid under the assumption of using green electricity. If grey electricity (based on current electricity mix) is used, the carbon dioxide emissions are three times higher than SMR.

### 3.1.3 Flexibility

The system flexibility, quantified as response time and load range shows that PEM, battolyser and LT SSAS based power to ammonia systems have a load range of 0 to 100% of nominal capacity and are able to ramp up from 0% to 100% in 40 minutes and turn down from 100% to 0% in 10 minutes. The total ammonia plant, including an electrolyser section and an ammonia synthesis section is limited in flexibility by the ammonia synthesis section. In case of HT SSAS and SOEC as the choice of electrolysis, power to ammonia systems have a load range of 50% to 100% and can ramp up in 25 minutes and turn down in 13 minutes. The ramp up time is limited by the NH<sub>3</sub> synthesis system, while the ramp down and the load range are limited by the electrolysers themselves. The main risks associated with dynamic operations are the damage of the NH<sub>3</sub> synthesis catalysts due to thermal cycling and the loss of containment due to H<sub>2</sub> embrittlement if the system is shut down and pressure is maintained. Furthermore, it can be concluded that due to the magnitude of the ramp up and turn down speeds of the full P2A system it is not possible to operate on the smaller 15 minute or imbalance markets for the Eemshaven site nor to use an SOEC or HT SSAS at the Goeree-Overflakkee sites. However, this does not apply for the battolyser operating in the battery mode.

### 3.1.4 Cost of Ammonia

The production costs of ammonia is evaluated for the year 2023 and 2030 with varying levels of fuel prices and renewable penetration. Figure 7 and Figure 8 show comparison between the different technologies and years [12].



Figure 7. Cost of ammonia in the year 2023 with low and high fuel price.



Figure 8. Cost of ammonia in the year 2030 with high renewable penetration low and high fuel price.

It is found that the production costs of ammonia in the year 2023 and 2030 is always higher for the electrochemical than for the SMR option. However, in the year 2030 with high renewable penetration, this is no longer the case. In the year 2030 with high renewable penetration the SOEC and battolyser are able to achieve lower ammonia production costs than the SMR. For the SOEC this can be attributed to its high efficiency and for the battolyser it is due to additional revenue generated by acting also as a battery for short term storage.

### 3.1.5 Cost Drivers

Evaluation of the CAPEX has identified that the cost drivers for the year 2023 are the electrolysers and in the year 2030 all systems apart from the battolyser continue to be driven by investments in the electrolyser costs. The cost breakdown for the PEM system in the year 2030 is shown in Figure 9.



Figure 9. Cost Breakdown of PEM P2A System in the year 2030.

In the year 2030 the cost driver for the battolyser system is the ammonia synthesis. This enables the system to benefit from economies of scale, whereby the cost scales to the power of 0.6 and not linearly. The OPEX excluding feedstock are dominated by the maintenance costs. Since this is taken as 2% of the CAPEX, the trends identified in the CAPEX also holds true for the OPEX. Additional costs are lifetime stack replacements costs. These vary between 60 and 65% of the electrolyser cost. The time to replacement is 80,000 hours of operation for low temperature units, i.e. the PEM and battolyser and 40,000 operating for the high temperature SSAS and SOEC. With the electrolyser costs being the cost drivers, the lifetime stack replacement costs can be as high as 39% of the initial CAPEX in some cases (500 MW<sub>e</sub> PEM and SSAS). If the intermittent operation of the PEM and battolyser are assumed to have limited or no impact on the performance, no stack replacement is required.

### 3.2 Energy Storage Benchmark

P2A is a way to store electrical energy in ammonia. This ammonia can later be converted back into electrical energy by combusting it in a Combined Cycle Gas Turbine (CCGT) power plant. A comparison is made with other methods for storing electrical energy on a seasonal level (TWh scale). A first selection round was performed to create a shortlist of storage methods with high potential for seasonal storage. Various options are compared, including secondary batteries, flow batteries, fly wheels, compressed and liquefied air, pumped hydro, thermal and chemical storage. The key performance indicators used for comparison are: volumetric energy density and power to power efficiency (or round trip efficiency). The power to power (P2P) efficiency is a measure of how much of the electrical energy that is supplied to the system can be returned back as electricity.

The result shows that only chemical storage methods have the desired energy density for seasonal storage applications. A detailed comparison of the various chemical storage options is performed by Nuon [13]. The results for the P2A systems with an volumetric energy density for ammonia of  $6.8 \text{ GJ}_{e} / \text{m}^{3}$ , are given in Table 2.

Table 2. P2P efficiency of ammonia	based	energy	storage.
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System type	P2P efficiency
PEM	29%
Battolyser	31%
SOEC	39%
LT SSAS	34%
HT SSAS	25%

The P2P efficiency of the battolyser for the electricity stored for short term in the battery functionality (so without conversion to ammonia) is 82 - 90%, therefore the actual P2P efficiency of the battolyser for a given year will depend on the it's utilization as an electrolyser and a battery. The reason for the differences between the technologies are related to the underlying ammonia production efficiency, this is detailed in section 3.1.1.

## 4. Conclusions and R&D Roadmap

It can be concluded that P2A has in the long term, the potential to contribute substantially to the carbon dioxide reductions targets since the  $CO_2$  avoided is 100% if considering ammonia production from green electricity.

The technology required for deployment of some power to ammonia systems is already available today. However, the economics are not favourable until the year 2030 with high renewable penetration. Evaluation of the CAPEX has identified that the cost drivers for the year 2023 are the electrolysers and in the year 2030 all systems apart from the battolyser continue to be driven by investments in the electrolyser costs (see section 3.1.5). The cost of the electrolysers for an electrochemical NH<sub>3</sub> plant is in some cases more than 60% of the total capital expenditure (CAPEX). Although electrolysis has been an industrial technology for many decades, to obtain the targeted market prices for NH<sub>3</sub> in 2030 performance improvement and cost reduction is needed. Back calculations show for the NUON case that the target costs for the electrolyser should be 300 €/kW. In all Stedin cases even without an electrolyser, the system is too expensive to operate [13].

#### Is this target feasible for the different technologies?

Projections from the European FCH-JU [14] show a decrease in PEM electrolyser costs from 921 EUR/kW in 2023 to 600 EUR/kW in 2030.For the battolyser an even lower purchased cost of 370 EUR/kW is predicted. The purchased cost of the SOEC & SSAS systems are estimated to be comparable with the PEM system costs. All projections show higher prices than the target, but recent developments in PEM fuel cells show that major cost reductions (to 150 EUR/kW) are possible with mass fabrication [15]

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

PEM electrolysers typically require expensive materials to achieve lifetimes and efficiencies comparable to commercial alkaline technologies. Durability has a double impact on the electrolyser economics. Reduced lifetime increases the capital cost because of depreciation is done over a shorter period of time but also because of the need to go to more expensive materials. Most R&D activities therefore focus on material and component developments. An illustration is the set of research priorities as presented by Hydrogenics [16] and shown in Table 3.

Table 2	Kovracoarch	priorition from	the workshop	(Degradation P	Durability in DEM	alactrolycic'	[17]
Table 5.	Key research	priorities from	the workshop	Degradation &	Durability III FLIVI	electionysis	[1/]

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

#### The R&D needs for the battolyser is indicated by TU Delft and a summary is given below.

"For the battolyser TU Delft has been calculating with limited power levels compared to the amount of electrode material (in MWh capacity) to keep the efficiency high (45 kWh/kg H<sub>2</sub>). The penalty in efficiency when doubling the power level in the same device during electrolysis is now about 4% (so 46.8 kWh/kg H2). A price reduction of the required electrolyser stack capabilities could therefore be obtained by choosing a 50% smaller MWh capacity and run it at a 100% higher power level. The discharge current cannot be increased by 100% for the full capacity in MWh, however, so it does lead to smaller battery capacity (although there we have a gain factor not yet accounted for of about 1.5 because we use the electrode material now ~50% more efficient than is possible in the old battery) The balance of plant will remain the same cost, however research will be performed to mitigate the efficiency loss altogether by gains on other fronts.

A second driver for cost reduction should be developing a large scale product of such battolyser and its materials inventory. Note that the raw materials cost are far below the 100 EUR/kWh in electrode materials. However further upscaling of battolyser technology will require a number of factors to be addressed. In principle we are dealing with a hybrid technology of two existing, mature, technologies: alkaline electrolysis and nickel iron batteries. To come to higher efficiencies it is advantageous to operate under pressure, as is done in alkaline electrolysis. The gas handling and electrolyte handling system, will be similar to what is available for alkaline electrolysers. The electronic system is like that of a large battery system, but simpler because there is no need for overcharge protections. The exact dimensioning of all components will be subject to further development. It is anticipated that upscaling can be performed without fundamental research needs. An scaled-up version will need testing in various applications as short term battery storage operating for grid balancing purposes, operating as battery on a 15 minutes basis of charge/discharge, as H<sub>2</sub> source for short and long duration and integrated with subsequent processing of the produced  $H_2$ . Also operational parameters like the temperature and pressure control, safety aspects, and gas quality, need testing in a real large scale test environment. Within an STW project developments and improvements are being investigated to come to further efficiency enhancements with respect to the materials use, cost of materials, and device layout. These developments may be incorporated in later scaled-up versions." – Prof. F. Mulder, TU Delft

The R&D needs for the SSAS has been elucidated after discussion with TU Delft. The current Solid State Ammonia Synthesis (SSAS) operate at high temperature and co-produce ammonia and hydrogen. Total energy efficiency of electricity to ammonia and hydrogen combined will be around 60-80%, with the ammonia and hydrogen being co-produced in a mole ratio of 1:3. The target for the SSAS is to move towards 65 to 70% total energy efficiency for the production of pure ammonia. Additional improvements are required in areas of material durability and operating

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

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