The Future of Ammonia Is Green

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Ammonia (NH_3) is a key feedstock for inorganic fertilizers that currently support food production for around half of the world's population. The vast majority of ammonia in use today is *conventional ammonia*, i.e. produced from fossil fuels such as natural gas. The **production of conventional ammonia** alone **accounts for around 1.8% of global carbon dioxide emissions** [1]. While chemically identical, *green ammonia* is produced with minimal carbon emissions using green hydrogen made by electrolyzers operating on renewable energy. Since hydrogen electrolysis accounts for more than 90% of the energy required to produce green ammonia [2], **the production of green ammonia is solely dependent on and can only be achieved through the production of green hydrogen.**

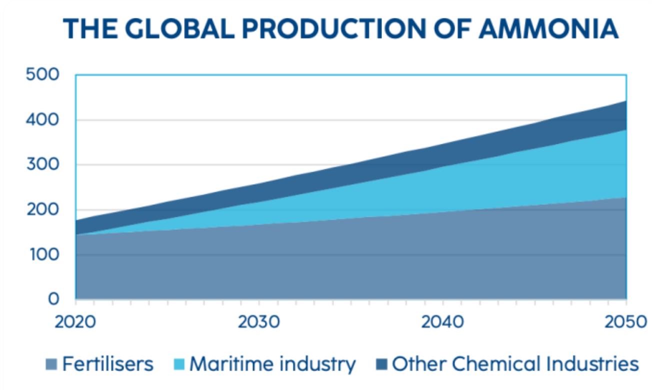

Figure 1. The growing market of ammonia production [3, 6].

Green ammonia is presently receiving a lot of attention **as a prospective carbon-free fuel for the maritime sector** [3, 4]. The European Green Deal and the recent Fit for 55 legislative package [5] have helped increase the demand for green ammonia in Europe and globally. This creates **a unique market opportunity for ammonia producers** who are willing to be first-movers in climate-friendly ammonia. This whitepaper gives an overview of green ammonia production benefits and its future potential.

Current global ammonia production is about **180 million tonnes per year** [3] with an average growth rate about 2% in the last five years [6] with China, Russia, India, and USA being the biggest producers. The maritime sector plans to adapt to ammonia as a fuel, expanding the current market volume by over 30 % (Figure 1). Until recently, low natural gas prices were the critical factor in conventional ammonia production operations.

Now, the CO_2 emissions related to ammonia production are becoming increasingly important, and first large-scale green ammonia production plants (e.g. the NEOM project in Saudi Arabia [7], and the Høst project in Denmark [8]) are in the design and construction phase. The CO_2 footprint of existing ammonia plants can be lowered by converting the plant into a hybrid plant, where the production of green and conventional ammonia is combined, taking full advantage of the economies of scale of existing ammonia synthesis infrastructure. **While the rising CO_2 taxes make the economics of conventional ammonia more challenging, the business case for green ammonia is becoming increasingly more attractive.**

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Conventional *vs* Green Ammonia Production Cycle

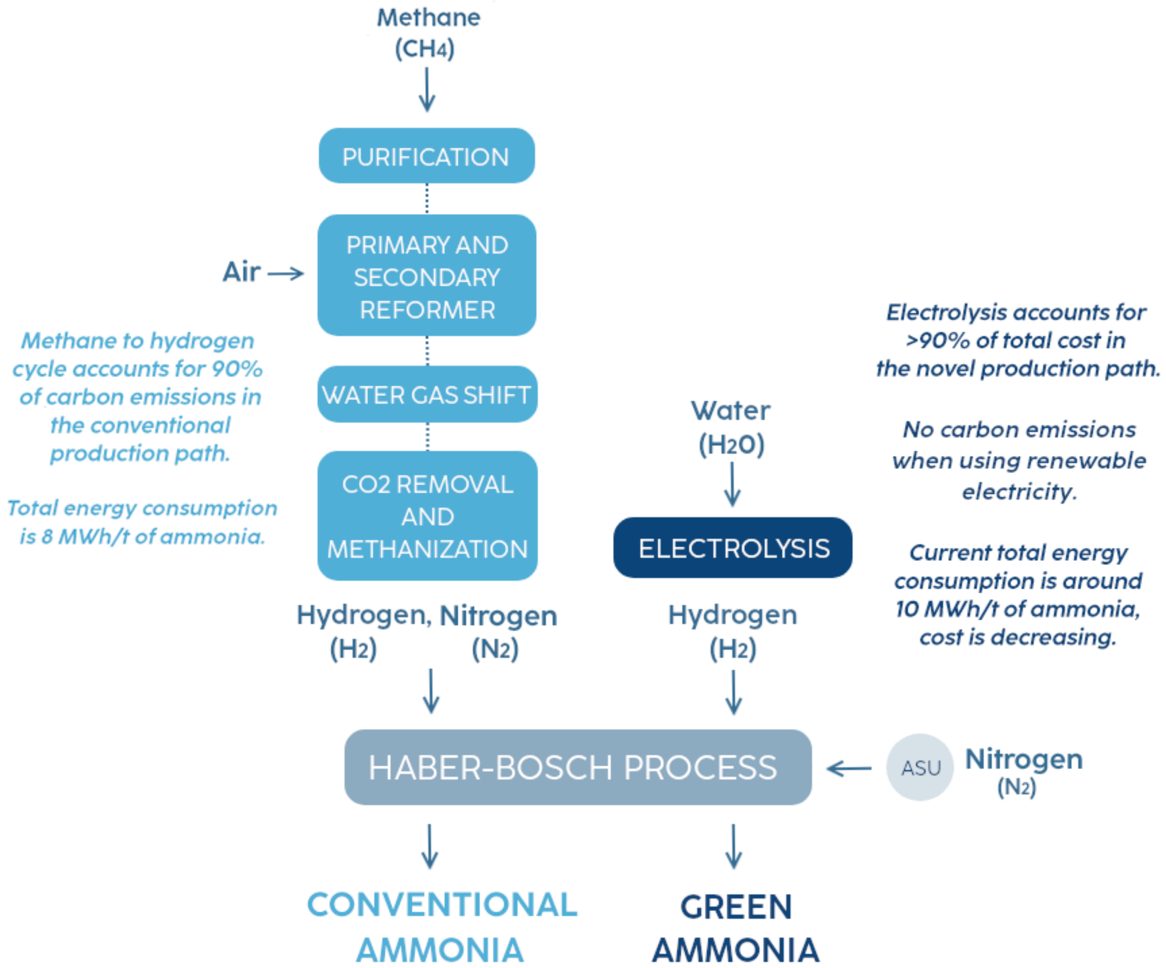

Figure 2. The Production cycles of conventional ammonia and green ammonia [2].

In the production cycle of conventional ammonia, methane (or another fossil fuel) is first reformed in the presence of steam and catalysts (Figure 2). Air is added to the reformer to achieve the required nitrogen to hydrogen ratio for the downstream Haber-Bosch synthesis step. Carbon monoxide (CO) produced in the reforming step is converted to CO_2 in the presence of water in the water-gas shift reactors, thus increasing the hydrogen yield. The resulting synthesis gas (N_2+H_2) is cleaned of CO, CO_2, and other impurities before the gas mixture is led into the ammonia synthesis loop (Haber-Bosch process, i.e. $N_2 + 3\ H_2 = 2\ NH_3$). [2].

In **the production cycle of green ammonia,** high purity water is used as input. Water is electrochemically split into hydrogen gas and oxygen gas using alkaline electrolysis cells (AEC). Nitrogen extracted from air using an air separation unit (ASU) is combined with hydrogen in the ammonia synthesis loop. The synthesis loop is very similar to the synthesis loop used in conventional ammonia production. **Green hydrogen production accounts for almost 94% of the total energy input in the process and is thus a central part of the green ammonia production cycle.**

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Alkaline electrolysis cell technology is the most mature of the prominent electrolysis technologies. The electrolysis process in alkaline cells takes place in strongly alkaline conditions, in a concentrated potassium hydroxide solution. Water reacts at the negative electrode (cathode) to form hydroxide ions and hydrogen. Hydroxide ions are transported through the separator onto the positive electrode (anode) where oxygen is released. The separator is used to avoid the mixing of produced gases.
The overall process is $2H_2O \rightarrow 2H_2 + O_2$.

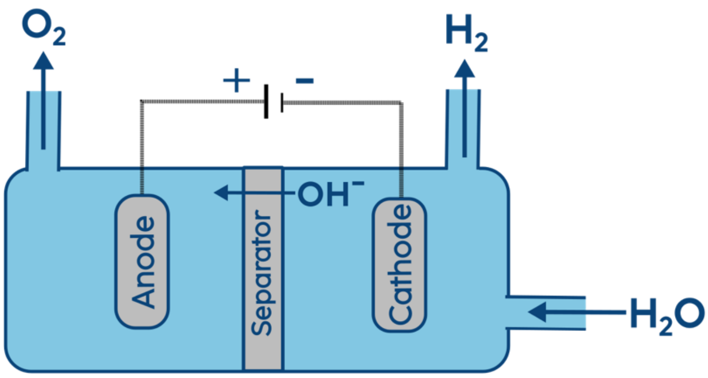

Figure 3. The working mechanism of an alkaline electrolysis cell [2].

Alkaline **technology** is **highly reliable** and with **decades of proven track record** in demanding industrial applications. **Stargate Hydrogen** electrolyzers boast highly-attractive CAPEX figures and the high electricity-to-hydrogen conversion efficiency results in competitive OPEX, making our solution ideal for use in green ammonia plants (see our product portfolio).

The future will be based on green ammonia

In a new wave of the energy revolution, ammonia is replacing fuels and energy carriers in all of the main business sectors. As an energy storage medium, ammonia is easily stored in large quantities as a liquid at modest pressures (10 – 15 bar) or refrigerated to -33°C. As a zero-carbon fuel, ammonia can also be used in fuel cells or by combustion in internal combustion engines, industrial burners and gas turbines [1].

Ammonia as a fuel and as an energy storage medium

Hydrogen and ammonia are closely related substances due to their properties, but in the light of hydrogen as a future alternative fuel, ammonia as a fuel in fuel cells and internal combustion engines (ICE) has been rather overlooked. Ammonia is a carbon- and sulfur-free fuel and it has an energy density comparable to fossil fuels [3] (see Figure 4). Even though NO_x and N_2O are still formed during the combustion of green ammonia in an ICE, they are easily removed using modern SCR technology [3]. **Recent studies have concluded that ammonia is the lowest-cost method and the most technologically viable option for transporting energy over long distances** [1, p24]. It has the best properties in terms of energy density, handleability and overall transportation efficiency.

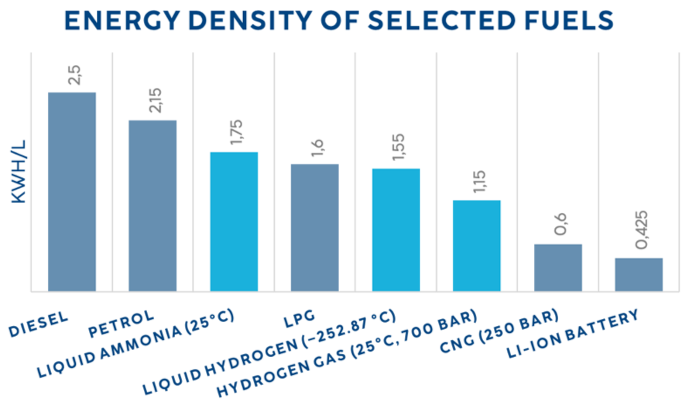

Figure 4. Energy densities of selected fuels, accounting for typical container properties and energy conversion technology efficiencies [1, p 30].

Maritime industry

International shipping accounted for about 2.2% of the total global anthropogenic CO_2 emissions, but the maritime industry is actively searching for climate-friendly alternatives [3]. Maersk, the largest container shipping line and vessel operator in the world, has dismissed the use of fossil fuels in new vessels and has proposed ammonia as a prospective fuel to be used in newly built vessels [3, 4]. In order **to meet 30% marine fuel demand by 2050, 150 million tonnes of additional ammonia production capacity will be needed** [3] (Figure 1).

Fertilizers

The fertilizer market is already a strong and growing market, accounting for 80% of today's ammonia demand [3]. The market for nitrogen fertilizer has reached 110 million tonnes and is estimated to increase 25% by the year 2030 [6]. In order to fulfill climate goals, conventional fertilizers need to be replaced with green fertilizers at a rapid rate.

Hydrogen Storage

When liquefied, ammonia contains 70% more hydrogen by volume than liquid hydrogen. These properties, along with ease of storage and transportation, make ammonia an attractive candidate for consideration for the storage and delivery of hydrogen. In contrast, to store hydrogen at scale it must be compressed to around 350 to 700 times atmospheric pressure, or cryogenically cooled to -253°C. **Consequently, the storage of hydrogen is more difficult, energy-intensive and expensive than storing ammonia** [1]. For these reasons, **ammonia is most likely to become one of the main storage media for hydrogen**.

The scale and cost of producing green ammonia

Taking the efficiencies and energy requirements of all the stages of green ammonia production into account, a 100 MW hydrogen electrolyzer is suitable for producing enough hydrogen for enabling the production of 224 tonnes of ammonia per day. **Approximately 10-11 MWh of electricity is required for the production of 1 tonne of green ammonia.**

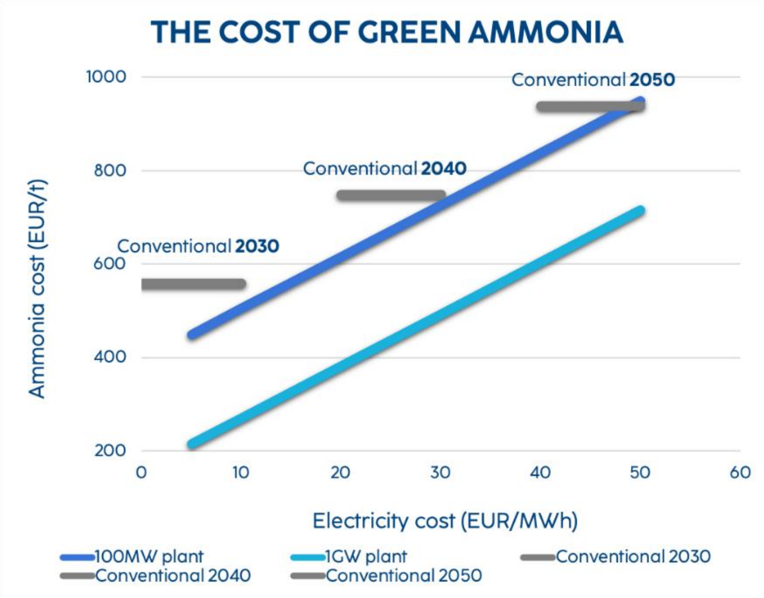

Figure 5. The Price of green ammonia [2, 3, 9, 10]

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Market vision

The price of producing green hydrogen primarily depends on the availability and price of green electricity, as well as whether the ammonia is produced at a level corresponding to 100 MW or 1 GW electrolysis capacity. As seen from the Figure 5, at an electricity price of 30 EUR/MWh, ammonia produced at a scale of 1 GW of electrolysis capacity, is already cost-competitive with conventional ammonia. Under otherwise identical conditions, a smaller, 100 MW based plant is presently still more expensive than ammonia produced using conventional methods.

In case intermittent renewable power is used for hydrogen generation, additional short-term hydrogen storage options may be needed to level out fluctuations in hydrogen production. In contrast to the production of conventional ammonia, **taxes on CO_2 emissions do not affect the production costs of green hydrogen.**

As the production costs of conventional ammonia are expected to increase (by linear forecast) to 400% of its present level **by the year 2030** as a result of surging carbon emission taxes, **green ammonia will become increasingly more profitable.** In regions with excellent access to renewable electricity and in regions where carbon emissions are under increasing scrutiny, **we expect green ammonia to reach price parity within the next 3-5 years.**

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