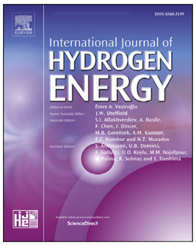
Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



# Power-to-ammonia in future North European 100 % renewable power and heat system

*Jussi Ikäheimo* [a,*], *Juha Kiviluoma* [a], *Robert Weiss* [b], *Hannele Holttinen* [a]

[a] *Power Systems and Renewables, VTT Technical Research Centre of Finland, FI-02044, VTT, Finland*
[b] *Ecoefficient Districts, VTT Technical Research Centre of Finland, FI-02044, VTT, Finland*

ARTICLE INFO

*Article history:*
Received 10 April 2018
Received in revised form
16 June 2018
Accepted 20 June 2018
Available online xxx

*Keywords:*
Renewable hydrogen
Large-scale integration of renewable power generation
Power-to-ammonia
Electrolysis
Energy storages
Hydrogen carriers

ABSTRACT

Power-to-gas and other chemicals-based storages are often suggested for energy systems with high shares of variable renewable energy. Here we study the North European power and district heat system with alternative long-term storage, the power-to-ammonia (P2A) technology. Assuming fully renewable power and heat sectors and large-scale electrification of road transport, we perform simultaneous optimization of capacity investments and dispatch scheduling of wind, solar, hydro and thermal power, energy storages as well as transmission, focusing on year 2050. We find that P2A has three major roles: it provides renewable feedstock to fertilizer industry and it contributes significantly to system balancing over both time (energy storage) and space (energy transfer). The marginal cost of power-based ammonia production in the studied scenarios varied between 431 and 528 €/t, which is in the range of recent ammonia prices. Costs of P2A plants were dominated by electrolysis. In the power and heat sector, with our cost assumptions, P2A becomes competitive compared to fossil natural gas only if gas price or $CO_2$ emission price rises above 70 €/MWh or 200 €/$tCO_2$.

## Introduction

The U.N. Intergovernmental Panel on Climate Change has estimated that human activity is responsible for the climate change with greater than 95% probability [1]. EU has set itself a long-term goal of reducing greenhouse gas emissions by 80–95%, when compared to 1990 levels, by 2050. There is thus a great urgency to develop and deploy carbon-neutral energy technologies.

Solar power and wind power have become affordable technologies for energy production but they are hindered by variability, seasonality and uncertainty. Balancing of renewable energy will pose a serious challenge to realizing a fully renewable energy supply. While efficient transmission and demand response can offer a partial solution, a number of mechanical, electrical, thermal, and chemical methods have been developed for storing electrical energy [2,3]. Chemicals-based storage offers the advantage of being able to store large amounts of energy for long periods of time. They also enjoy substantial design flexibility [4], e.g. storage size and power capacity are easy to separate. In many cases, chemicals-based energy storage are not merely storages but also act in a dual role as producers of synthetic fuels or chemicals. Developing synthetic fuels on a global scale is a key enabling element in decarbonizing also other sectors besides the power and district heating sectors.

---

* *Corresponding author.*
E-mail address: Jussi.ikaheimo@vtt.fi (J. Ikäheimo).

https://doi.org/10.1016/j.ijhydene.2018.06.121

Please cite this article in press as: Ikäheimo J, et al., Power-to-ammonia in future North European 100 % renewable power and heat system, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.06.121

**Nomenclature**

| | |
|---|---|
| ASU | Air Separation Unit |
| CCGT | Combined Cycle Gas Turbine |
| CCS | Carbon Capture and Storage |
| CHP | Combined Heat and Power |
| ETS | Emissions Trading System |
| EV | Electric Vehicle |
| GDP | Gross Domestic Product |
| HHV | Higher Heating Value |
| LHV | Lower Heating Value |
| OCGT | Open Cycle Gas Turbine |
| P2A | Power-to-ammonia |
| PEM | Proton Exchange Membrane |
| PV | Photovoltaic |
| STP | Standard Temperature and Pressure |
| $\eta_{ely,th}$ | Electrolyzer efficiency |
| $H$ | Electrolyzer hydrogen output |
| $H_{max}$ | Electrolyzer maximum hydrogen output |
| $h$ | Specific hydrogen output |
| $J_0$ | Electrolysis nominal current density |
| $P_{ely}$ | Electrolyzer power input |

Presently, water electrolysis is seen as the most feasible technology in power to chemicals conversion [5]. Hydrogen has been long studied as an energy carrier. Cost and technical characteristics of water electrolysis technologies as well as future trends are presented in reviews [6–8], indicating that attractive investment costs and performance are within reach before 2030. However, hydrogen storage is expensive and inconvenient and therefore other chemicals which serve as hydrogen carriers must be considered [4]. At least two alternative routes for stationary chemical hydrogen storage can be defined: carbon and nitrogen chemistries [5]. The former includes the conversion of power via hydrogen into methane, called power to gas (P2G) [9], or into methanol. Both add energy losses compared to pure hydrogen as energy carrier. Still, P2G has the advantage of existing infrastructure for methane transport and storage, compared to hydrogen which requires new challenging infrastructure [10,11].

The second route is to convert hydrogen into nitrogen-based fuels. The simplest such fuel is ammonia ($NH_3$), hence the term ammonia economy [5]. $NH_3$ is the second largest synthetic inorganic commodity produced worldwide [12], with 80% of the production used by the fertilizer industry. $NH_3$ carries the nitrogen component to manufactured nitrogen fertilizers, which currently contribute to feeding around half of the population in the world [13]. $NH_3$ is also used in the production of nitric acid via the Ostwald process and as a refrigerant. $NH_3$ is normally produced in the Haber-Bosch process from elemental nitrogen and hydrogen derived mainly from steam-reformed natural gas. Steam reforming of the natural gas has high energy and carbon intensity [14]. EU average ammonia plants consume 35.2 GJ (LHV) natural gas per tonne of $NH_3$, emitting 1.9–2.1 tonnes of $CO_2$ per tonne of $NH_3$ produced [15,16]. If hydrogen is produced by other fossil feedstock or coal gasification the $CO_2$ emission is substantially higher [17]. Conventional ammonia production alone is responsible for 0.93% of global greenhouse gas emissions [13].

$NH_3$ produced from renewable hydrogen can reduce greenhouse gas emissions [18,19]: the Haber-Bosch process can also be fed with renewable hydrogen, which according to conceptual studies could be obtained from biomass gasification [20], or via water electrolysis from renewable power like solar [21], wind [22,23], or hydro power [24]. The combined application of water electrolysis and Haber-Bosch process is called power-to-ammonia (P2A) technology. The advantage of nitrogen-based fuels is that nitrogen, abundant in the atmosphere, can be used as feedstock, whereas methanation or methanol production require $CO_2$. $CO_2$ may be extracted from point sources if additional purification steps are used to prevent degradation of methanation catalysts. Also separation of $CO_2$ from the atmosphere has been considered as an alternative, but the energy requirement of $CO_2$ separation from the atmosphere is an order of magnitude greater than that of nitrogen [5], and it has considerable cost uncertainty as technology is immature.

$NH_3$ can be combusted in fuel cells [25], reciprocating engines or gas turbines. Although it cannot be easily used in existing Otto cycle engines because its narrow flammability range, $NH_3$-fired engines have been built for buses already during World War II [26]. $NH_3$ can be directly combusted in solid oxide fuel cells [26]. Another possibility, which avoids the formation of nitrous oxide in $NH_3$ combustion, is the decomposition of $NH_3$ into its elements by catalytic cracking or the sodium-amide process [27]. The produced hydrogen can then be combusted in fuel cells or gas turbines.

$NH_3$ has a number of clear advantages as synthetic fuel and energy storage. It contains no carbon and therefore its combustion does not produce $CO_2$. It can be easily as liquid stored in atmospheric pressure by cooling to $-33\,^\circ C$ or pressurized at 9 bar in room temperature [27,28]. The cost of storage is low, and can be densely stored for large energy amounts without any significant losses [29]. A typical liquid $NH_3$ storage tank in the Corn Belt, USA, has a capacity of 30,000 Mt, equal to 190 GWh as $H_2$ reformed from $NH_3$, with estimated capital cost of only ~0.1US$/kWh [29]. Large existing infrastructure is in place for the transportation and storage of $NH_3$. $NH_3$ is regularly transported in carbon-steel pipelines, rail cars, trucks and ships [29]. Its disadvantage is toxicity, which however, is not a major problem in power generation because there are well-established handling procedures and the fuel's historical safety record is good [12]. $NH_3$ has a pungent odor which acts as a warning of dangerous level of exposure. In the fertilizer industry, $NH_3$ produced from renewable hydrogen can reduce greenhouse gas emissions:

$NH_3$-derived chemicals such as hydrazine ($N_2H_4$), ammonia borane ($NH_3BH_3$), ammonia carbonate ($(NH_4)_2CO_3$) and urea ($CO(NH_2)_2$) and can be mentioned as potential $NH_3$ storage, indirect $H_2$ storage or alternative fuels [25]. Fuel cells using directly these $NH_3$ related materials or their solutions have been demonstrated, and safety is not an issue if $NH_3$ is stored in solids such as $(NH_4)_2CO_3$ or $CO(NH_2)_2$ [25].

The ammonia economy has been studied and reported in the literature from the perspective of process modeling and simulation [30–32], use of ammonia as energy storage in an islanded system [28], value chain analysis of avoiding grid

Please cite this article in press as: Ikäheimo J, et al., Power-to-ammonia in future North European 100 % renewable power and heat system, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.06.121