



System-Level Analysis of Energy Efficiency in a Power-to-Ammonia-to-Hydrogen Cycle: A Case Study

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ABSTRACT

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This thesis assesses the energy efficiency of a Power-to-Ammonia-to-Hydrogen (P2A2H) chain, where electricity is converted to hydrogen via electrolysis, then synthesized to ammonia, stored and transported, and, finally, reconverted to hydrogen through cracking and purification processes. A thermodynamically consistent and simplified model was used on a 1 kg delivered hydrogen basis with the use of literature data for the specific electricity consumption for each stage of the chain.

The obtained values for the central case indicate a total electricity demand of 59.45 kWh per kilogram of hydrogen delivered that corresponds to 56% (LHV) round-trip efficiency and lies within the range of 50 – 60% range, reported for similar systems. The most dominant energy consuming stages are water electrolysis and ammonia cracking, while other processes combined showed only a minor contribution. The transparent and stage-resolved framework is the main innovation, which combines process breakdown with a systematic sensitivity analysis and comparison of alternative hydrogen carriers, clearly highlighting electrolysis

efficiency and cracking energy demand as the key levers for improving P2A2H efficiency. The results, interpreted in the context of current large-scale projects such as NEOM, H2Global and Project Yuri, position chain as a medium efficiency, but logistically an attractive option for long distance renewable hydrogen transport and provide a practical benchmark for future technology and system development.

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SYMBOLS AND ABBREVIATIONS

Roman characters

T	temperature	°C, K
E	energy consumption	kWh
e	specific energy consumption	kWh/kg
m	mass	kg
M	molar mass	kg/mol
n	amount of substance	mol
V	volume	m ³ , Nm ³
V_m	molar volume	m ³ /mol
D	transport distance	km
R_{H_2}	hydrogen recovery	

Greek characters

η	efficiency
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Abbreviations

ASU	Air Separation Unit
AWE	Alkaline Water Electrolysis
CGH ₂	Compressed Gaseous Hydrogen
DBT	Dibenzyl toluene
LH ₂	Liquid Hydrogen
LHV	Lower Heating Value
LOHC	Liquid Organic Hydrogen Carrier

NO _x	Nitrogen Oxides
P2A2H	Power-to-Ammonia-to-Hydrogen
PEM	Proton Exchange Membrane
PSA	Pressure Swing Adsorption
SOEC	Solid Oxide Electrolysis Cell

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DECLARATIONS

Turnitin

The originality of this thesis has been reviewed with the Turnitin similarity checking service.

AI usage

The author of this thesis, Arturs Zusters, used the following AI-tools during the preparation of the thesis:

1. AI tool name: ChatGPT by OpenAI (San Francisco, California)

a. Purpose of use:

To support linguistic accuracy and coherence.

b. Explanation of the use of the tool:

ChatGPT was used to refine sentence structure, grammar and wording to improve clarity, consistency and academic style. The scientific content, calculations and conclusions were made independently by the author.

2. AI tool name: Perplexity by Perplexity AI, Inc. (San Francisco, California)

a. Purpose of use:

To assist in drafting the overall structure of the thesis.

b. Explanation of the use of the tool:

Perplexity was used to propose alternative outlines, headings and logical ordering of chapters and subsections, which helped to organise the material into a clear and coherent structure. The final thesis structure and all methodological choices were decided independently by the author.

Responsibility

The author, Arturs Zusters, takes full responsibility for the content of this thesis and has reviewed and edited the content generated by the possible use of AI too.

1 Introduction

The transition to a sustainable and low-carbon energy system requires large-scale integration of variable renewable electricity and deep decarbonization of sectors that are difficult to electrify directly, such as heavy industry, long-distance transportation and seasonal heating. Therefore, hydrogen has been considered as a flexible energy carrier that can be produced from renewable electricity and used without direct CO₂ emissions, allowing both sector-coupling and long-duration energy storage (Dawood et al., 2020). At the same time, the performance of hydrogen-based systems is significantly affected by its physical properties, especially its low volumetric energy density, which result in additional energy usage for compression, liquefaction or conversion into other hydrogen-rich substances (Sarmah et al., 2023).

Ammonia has emerged as a promising hydrogen carrier, which can help mitigate hydrogen related challenges. Liquid ammonia contains a high amount of hydrogen per unit volume and, therefore, can be stored and shipped at moderate pressures and temperatures when compared to liquid hydrogen (Cardoso et al., 2021) This thesis analyses the performance of the Power-to-Ammonia-to-Hydrogen (P2A2H) chain, which consists of several stages: renewable electricity is used to produce “green” hydrogen, which is then converted to ammonia via Haber-Bosch process, transported over long-distance and later converted back to hydrogen by cracking. (Giddey et al., 2017)

Such systems require several extra steps of converting one substance into another, which always involve energy losses and, therefore, reduce “round-trip efficiency”, defined here as the ratio of useful hydrogen energy output to electricity input. Recent studies report a wide range of efficiencies for ammonia-based systems, which depends on the performance of electrolysers and crackers, the transport distance and final use of hydrogen. (Portarapillo et al., 2025) For this reason, it is important to reveal potential energy losses within a P2A2H chain and how sensitive the overall efficiency is to key assumptions.

The aim of this thesis is to conduct a system-level analysis of the energy efficiency of a Power-to-Ammonia-to-Hydrogen cycle. The main steps of the chain create a simple, but thermodynamically consistent model with the following stages: water electrolysis, air separation, Haber-Bosch ammonia synthesis, ammonia storage and transport, ammonia

cracking and then hydrogen purification. The data from the literature and a common basis of 1 kg of delivered hydrogen (LHV 33.3 kWh/kg) are used to define simplified assumptions for the specific electricity consumption, the total electricity demand and resulting round-trip efficiency. A sensitivity analysis provides an overview of how changes in key parameters affect the overall performance. The obtained results give a clear benchmark for comparison with alternative hydrogen transport options and future improvements in P2A2H technology.

2 Objectives and Motivation

This section outlines the motivation behind this research and defines specific objectives and scope of this thesis. First, the broader energy transition context and the key challenges associated with hydrogen storage and transport are introduced and discussed to justify the focus on the Power-to-Ammonia-to-Hydrogen chain. Next section presents the research objectives, which are stated clearly for the guidance purposes of the subsequent analysis in following chapters.

2.1 Research Motivation

Current energy industry is undergoing a rapid shift driven by the need to reduce greenhouse gas emissions and integrate large scale renewable electricity generation. Global renewable energy capacity reached 3.42 TW in 2024 and is projected to exceed 11 TW by 2035 and electrolysis capacity already reaching 520 GW worldwide. (IEA, 2024) While this development is directed towards the challenge of decarbonising electricity supply, it simultaneously creates a new challenge, where there is a spatial mismatch in production of renewables and its demand. Heavy industry, long-distance maritime transport and seasonal heating cannot be easily electrified and, therefore, require flexible, storable and transportable energy carrier (Capurso et al., 2022).

Hydrogen has been considered as a key enabler of deep decarbonization as it has the ability to store renewable electricity in chemical form and furthermore release it without direct CO₂ emissions (Dawood et al., 2020). Nevertheless, the practical deployment of hydrogen is still constrained by its low volumetric density, which requires energy intensive compression to 700 bar, cryogenic liquefaction to -253 °C or conversion to a hydrogen rich chemical compound, which allows efficient storage and transport (Sarmah et al., 2023). Such physical limitations make long-distance hydrogen transport costly and technically challenging, especially without a dedicated pipeline infrastructure.

Ammonia (NH₃) has emerged as one of the most promising solution to the problem described above. Hydrogen content is around 17 – 18% by mass and liquefaction temperature is -33 °C at atmospheric pressure. Moreover, ammonia offers a higher volumetric hydrogen density

of 100 – 110 kg_{H2}/m³ compared to compressed or liquefied hydrogen alternatives. (Chatterjee et al., 2021)

Despite the growing interest, the Power-to-Ammonia-to-Hydrogen pathway involves multiple conversion steps, which result in energy losses that reduce the overall round-trip efficiency of the chain. Recent studies report varying energy efficiencies, typically between 50 – 60% on a lower heating value basis when hydrogen is the final output (Giddey et al., 2017) However, the relative contribution of each stage and the overall efficiency sensitivity to key parameters are not always clearly separated in the literature, which makes it difficult to identify where efficiency improvements would have the greatest impact and compare to the P2A2H pathways systematically against alternative hydrogen options.

Therefore, the motivation for this thesis is driven by the need for a clear, transparent and thermodynamically consistent system level analysis of the P2A2H chain, which can serve as a benchmark for evaluating current technology performance and guiding future improvements.

2.2 Research Objectives and Scope

The aim of this thesis is to conduct a system level energy efficiency analysis of the Power-to-Ammonia-to-Hydrogen cycle. The following specific objectives are addressed:

- To build thermodynamically consistent model of the P2A2H chain based on 1 kg of delivered hydrogen (LHV = 33.3 kWh/kg).
- To quantify the specific electricity consumption at each stage: water electrolysis, air separation, Haber-Bosch ammonia synthesis, ammonia storage and transport, ammonia cracking and hydrogen purification.
- To calculate the overall round-trip efficiency of the P2A2H cycle on an LHV basis.
- To perform a sensitivity analysis on key performance parameters, which accounts for electrolyser efficiency, cracking energy and transport distance.
- To provide a performance benchmark for comparison with alternative hydrogen transport and storage options.

Finally, the scope of this thesis is limited to energy efficiency analysis and does not include economic assessment, equipment design or lifecycle emission analysis. All input data are derived from published scientific literature and techno economic reports to ensure transparency and reproducibility.

3 Theoretical Background

This section focuses on providing concepts needed to understand and evaluate the Power-to-Ammonia-to-Hydrogen chain. The first section introduces hydrogen as an energy carrier, with emphasis on its physical properties, advantages and limitations in a large-scale energy system. The following section presents ammonia as a hydrogen vector, highlights its storage and transport characteristics, and gives a brief comparison with alternative options. Finally, recent work on P2A2H is reviewed to show how such systems are utilised in practice.

3.1 Hydrogen as Energy Carrier

Hydrogen is considered a key clean energy carrier due to its low-carbon energy source production and use without direct CO₂ emissions (Dawood et al., 2020). Moreover, hydrogen allows the temporal and spatial redistribution of renewable electricity through power-to-hydrogen routes, which can be supported with large-scale wind and solar power systems. In addition, hydrogen's established role as a feedstock in refining and ammonia production is now being extended to the decarbonisation of transport, industry and power generation, especially in the challenging direct electrification sectors. (Capurso et al., 2022)

From a thermodynamic perspective, hydrogen has a high gravimetric energy density and the number of lower heating value (LHV) of roughly 120 MJ/kg, which is significantly higher than conventional hydrocarbon fuels have on a mass basis (Dawood et al., 2020). On the other hand, hydrogen becomes challenging when it comes to storage and transportation, due to its small molecular size and low-ambient volumetric density. This usually involves high-pressure compression, liquefaction and conversion into hydrogen-rich materials and possible chemical carriers (Sarmah et al., 2023). Recent studies place a strong emphasis on the hydrogen's usefulness mostly as a flexible energy carrier, highly dependent on the chosen storage and transport methods (Capurso et al., 2022). Existing infrastructure for ammonia production, storage and shipping, initially developed for the fertilizer industry, significantly lowers the deployment costs and timeline compared to building completely new infrastructure for hydrogen (Spatolisano et al., 2023). Such advantages have driven a rapid development of real-world green ammonia projects such as the NEOM project in Saudi

Arabia. They aim to produce up to 600 tonnes per day of carbon free hydrogen in the form of green ammonia, using 4 GW of integrated wind and solar capacity. (NGHC, 2025) Moreover, Envision's facility in Inner Mongolia, China is already delivering 320 000 t/year of green ammonia from off-grid renewables (Energy Institute, 2025).

3.2 Water Electrolysis Technologies

Water electrolysis is considered as a key technology that links renewable electricity to hydrogen. The technology market consists of several electrolyser types that are commercially available or in the development stage, each with different operating conditions, efficiencies and levels of technological maturity (Buttler & Spliethoff, 2018). The key technologies relevant for large-scale green hydrogen production, are alkaline water electrolysis (AWE), proton exchange membrane (PEM) and solid oxide electrolysis (SOEC).

The most mature and widely used technology from the list is alkaline electrolysers, which employ an aqueous alkaline electrolyte and operate at temperatures in 60 – 90 °C band and pressures up to 30 bar (Buttler & Spliethoff, 2018). While AWE systems are robust and use low-cost materials, which is an attractive option for large plants, they also have lower current densities and limited dynamic operating range, when compared to PEM units. On the other hand, PEM electrolysers use a solid polymer membrane as electrolyte and operate at similar temperatures. Moreover, it can achieve higher current densities, better response time and outlet pressures, which is considered as an advantage for integration with variable renewable generation (Dawood et al., 2020). PEM units have several drawbacks such as high capital costs and the use of scarce materials in catalysts and membranes. Finally, the solid oxide electrolysis systems operate at much higher temperatures, typically 600 – 800 °C and can potentially reach very high efficiencies by utilising waste heat. However, the technology is still in early development phase and face several issues related to system integration and durability. (Buttler & Spliethoff, 2018; JRC, 2025)

Current large-scale alkaline and PEM electrolysers require 50 – 60 kWh of electricity per kilogram of hydrogen produced on average, which corresponds to roughly 60 – 70% on a lower heating value basis (JRC, 2025). In this thesis, a generic large-scale alkaline/PEM system was modelled with an overall efficiency of 65%, which represents a realistic and non-optimistic operating point within the range. This approach neglects specific commercial

technology and focuses on the role of electrolysis in the P2A2H chain and remain consistent with reported performance data from the literature.

3.3 Ammonia as Hydrogen Vector

In the future hydrogen economy, ammonia is considered as one of the most promising vectors for hydrogen storage and transportation (Chatterjee et al., 2021). Each mole of NH_3 (ammonia) contains 1.5 mol of hydrogen, which corresponds to around 17 – 18% of hydrogen content and therefore liquid ammonia reaches volumetric hydrogen densities of 100 – 110 $\text{kg}_{\text{H}_2}/\text{m}^3$, which is significantly larger than many alternatives (Chatterjee et al., 2021). An additional advantage of ammonia is liquefaction temperature of $-33\text{ }^\circ\text{C}$ and moderate pressure, which makes it less energy-intensive compared with liquid hydrogen. The existing global ammonia infrastructure significantly reduces costs and makes it more appealing for hydrogen use. (Spatolisano et al., 2023)

From an energy-systems perspective, ammonia is considered as an attractive option for long-distance shipping and storage of renewable hydrogen due to its high volumetric density and established logistics (Cardoso et al., 2021). The density is around 3.8 – 4 MWh/m^3 and is slightly higher than liquid hydrogen if expressed on a hydrogen LHV basis and require less cryogenic conditions. Furthermore, ammonia can be cracked at the point of use to release the hydrogen for either conventional fuel cells or direct use in combustion systems or high temperature fuel cells, bringing multiple options on the utilization for energy conversion. (Spatolisano et al., 2023; Chatterjee et al., 2021)

On the other hand, the use of ammonia as a hydrogen vector introduces several challenges such as energy penalties during cracking and synthesis stages, catalyst requirements for efficient decomposition and safety concerns around its toxicity and NO_x emissions (Chatterjee et al., 2021). Such obstacle drives the research on a topic of a system-level analysis of round-trip efficiency, such as Power-to-Ammonia-to-Hydrogen cycle, which is investigated in this thesis.

3.4 Comparison of Hydrogen Carriers

This sub-section focuses on comparison between several hydrogen carrier options for large scale storage and transport. The most discussed alternatives include compressed gaseous hydrogen (CGH₂), liquid hydrogen (LH₂), ammonia (NH₃) and liquid organic hydrogen carriers (LOHCs), each offering different trade offs between energy density, storage conditions, infrastructure requirements and round-trip efficiency (Sarmah et al., 2023).

Compressed hydrogen has a volumetric density of around 1.3 MWh/m³ at 700 bars, which is significantly lower than ammonia at 3.8 – 4 MWh/m³, making long-distance shipping of compressed hydrogen economically unattractive (Cardoso et al., 2021). At the same time, liquid hydrogen has higher volumetric density of approximately 2.4 MWh/m³, however, it requires cryogenic storage at -253 °C, which demands highly specialised and expensive infrastructure with significant boil-off losses during transport (Spatolisano et al., 2023). LOHCs, such as dibenzyl toluene (DBT), can offer safe handling at ambient conditions and volumetric densities, when compared to ammonia, but, at the same time, require high-temperature dehydrogenation at the point of use and a return logistic chain for the carrier liquid, which is costly and complex (Chatterjee et al., 2021)

Ammonia ultimately combines several practical advantages such as high volumetric hydrogen density, well-established global infrastructure, moderate liquefaction conditions and the absence of a return carrier stream. The main drawbacks include energy penalties associated with cracking and purification at the destination, which reduces overall round-trip efficiency compared to direct pipeline transport of hydrogen. Table 1 summarises the key characteristics of the main hydrogen carrier options for comparison.

Table 1. Comparison of hydrogen carrier options (Chatterjee et al., 2021; Spatolisano et al., 2023; Sarmah et al., 2023)

	Compressed H ₂	Liquid H ₂	Ammonia (NH ₃)	LOHC
Volumetric H ₂ density [kg _{H2} / m ³]	~40	~71	~100 – 110	~57
Storage Conditions	Ambient temperature	-253 °C, 1 bar	-33 °C or 10 bar	Ambient
Infrastructure maturity	Limited	Very limited	Well-established	Emerging
Approximate round-trip efficiency (H ₂ output)	~70 – 80%	~60 – 70%	~50 – 60%	~40 – 55%

This comparison highlights that no single hydrogen carrier is optimal across all criteria. However, the most pragmatic and scalable option, due to established infrastructure and possibility for long-distance intercontinental transport, is still ammonia, which justifies its selection as the focus of this thesis.

3.5 Current Power-to-Ammonia-to-Hydrogen Systems

The main focus of the recent research on Power-to-Ammonia-to-Hydrogen systems is shed on integration of renewable electricity, water electrolysis, ammonia synthesis and cracking into coherent value chains with aim of long-distance transportation and storage. Such systems typically consist of electrolyzers with cryogenic air separation units and electrified Haber-Bosch loop to produce “green” ammonia, which is then transported and reconverted back to hydrogen using catalytic cracking. (Giddey et al., 2017) Design studies highlight the importance of connection with variable renewable energy, as both electrolyser and Haber-Bosch loop should respond to fluctuating power supply and maintain ammonia production targets. (Cameli et al., 2024)

There are several techno-economic and energy system assessments, which quantify the round-trip efficiency of Power-to-Ammonia-to-Hydrogen chain. Depending on electrolyser

performance, transport distance and the end-use conversion technology, the electricity-to-electricity round trip efficiency ranged from 20 – 40% for fully renewable systems where green ammonia is produced from green hydrogen. Higher efficiencies (50 – 60%) are obtained if the analysis stops at hydrogen output instead of electricity generation, which is relatively in-line with the central values of this thesis for the P2A2H cycle on a hydrogen LHV basis. Moreover, recent studies suggest that ammonia can offer a competitive advantage in transport economics due to its high volumetric energy density and existing infrastructure, even if its round-trip efficiency is lower than the pipeline-transported hydrogen. (Giddey et al., 2017) Current studies and ongoing work on P2A2H systems focus mainly on improving the efficiency of water electrolysis and ammonia cracking – two main energy-intensive steps, parallelly optimising plant integration and operating strategies for renewable energy input (Cameli et al., 2024). Such developments provide strong technical and analytical background for the system-level performance assessment, which is done in this thesis.

3.6 Real-World Projects and Demonstrations

The growing interest in Power-to-Ammonia-to-Hydrogen systems is presented not only in the academic research, but also in the large-scale industrial projects worldwide. These developments confirm the fact that the P2A2H pathway is transitioning from a theoretical concept into commercially deployed energy chain, which reinforces the relevance and practical value of the efficiency analysis conducted in this thesis.

3.6.1 NEOM Green Hydrogen Project (Saudi Arabia)

The NEOM Green Hydrogen Project is developed by NEOM Green Hydrogen Company (NGHC), which is an equal joint venture between ACWA Power, Air products and NEOM. It represents the world's largest green hydrogen facility under construction and located in the north-west of Saudi Arabia.



Figure 1. NEOM Green Hydrogen plant (NGHC, 2025).

The plant integrates 2.2 GW of solar and 1.6 GW of wind capacity to power a large-scale electrolysis system using ThyssenKrupp technology with nitrogen supplied by Air Products cryogenic air separation unit. (ACWA Power, 2024) In 2027, the facility is projected to produce 600 tonnes per day of carbon-free hydrogen, which will be converted into up to 1.2 million tonnes per year of green ammonia for export to global markets under a 30-year off-take agreement with Air Products. According to NGHC (2025) project reached 80% construction completion across all sites, which includes the green hydrogen facility, wind and solar farms, and transmission grid. With total investment of 8.4 billion USD, this project demonstrates commercial viability of integrating large-scale renewable generation with the full P2A2H chain at an unprecedented scale.

3.6.2 H2Global Initiative (Germany)

The H2Global initiative, backed by the German Federal Ministry of Economic Affairs and Climate Action, was established to fix the cost gap between green hydrogen production and the price European consumers are willing to pay, using a so-called “double auction model”. The first pilot auction concluded in July 2024 with Fertiglobe, a joint venture between ADNOC and OCI Global, winning a contract to supply green ammonia from its plant in Ain Sokhna, Egypt to European buyers through port of Rotterdam, Netherlands.

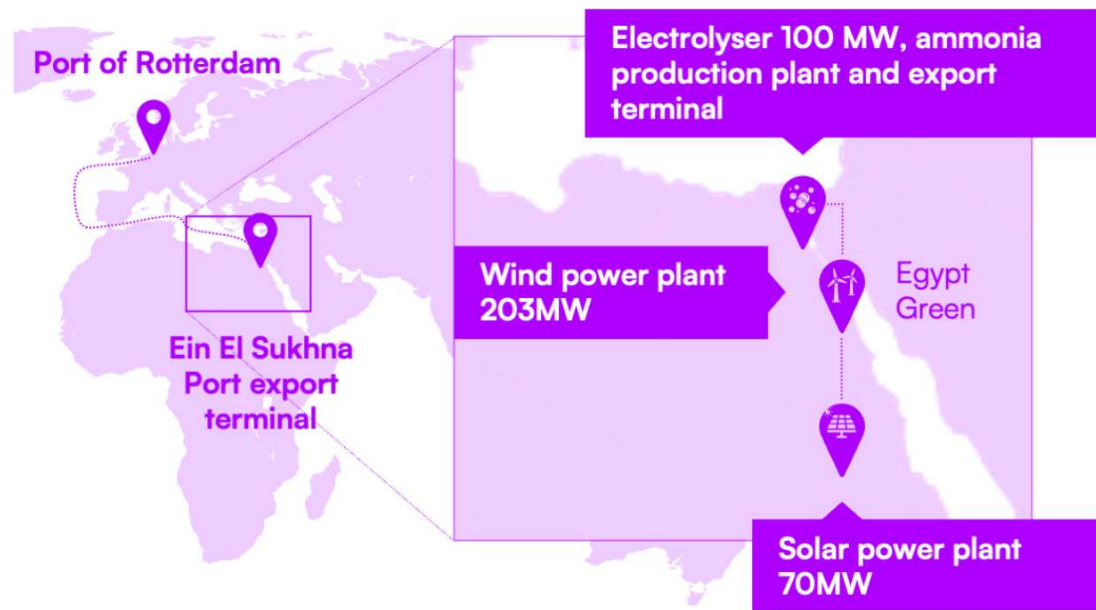


Figure 2. The Fertiglobe supply chain (Pearce, 2024).

The estimated time for deliveries is scheduled for 2027, where 19 500 tonnes will be transferred and 397 000 tonnes by 2033 with a maximum contract value of 397 million euros. (Pearce, 2024) This project is particularly significant as it establishes a real commercial framework for intercontinental green ammonia trade as a hydrogen vector, which is directly reflected in the P2A2H supply chain analysed in this thesis.

3.6.3 Project Yuri (Australia)

In Western Australia, Yara Clean Ammonia and ENGIE reached a final investment decision in 2022 on Project Yuri, which is a renewable hydrogen facility located adjacent to Yara's existing Pilbara ammonia plant. Initially, the project uses a 10 MW electrolyser power by on-site solar PV and battery storage to produce approximately 625 tonnes per year of renewable hydrogen, which is then blended into existing ammonia production stream to displace fossil fuel-derived feedstock (ARENA, 2022).



Figure 3. Yuri ammonia production facility in Karratha (ENGIE, 2022).

The electrolysis capacity is estimated to scale up to 500 MW by 2030 alongside a new 800 000 tonne per year ammonia plant, which will make Pilbara one of the largest renewable ammonia export hubs in the Asia-Pacific region (Atchison, 2022). This project shows how existing ammonia infrastructure can be progressively decarbonised by integrating renewable hydrogen, which follows the same P2A2H logic applied in this thesis.

3.6.4 Common Themes and Relevance

Across all three above mentioned projects, several common characteristics have been identified. First, ammonia is consistently chosen as the preferred hydrogen transport medium due to its high volumetric density, moderate storage conditions and compatibility with existing port and storage infrastructure. Second, water electrolysis is powered by renewable electricity, coming mostly from wind or solar energy, and utilised as the primary hydrogen production method, consistent with the model built in this thesis. Third, the range from tens of millions to several billions in investments indicates the importance of having clear efficiency benchmark to guide technology selection and system optimisation. The analysis presented in this thesis provides a directly applicable framework for understanding and evaluating performance of such projects.

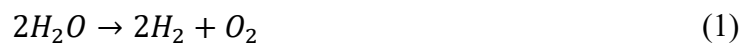
4 Methodology and Calculations

In this section, the performance of the Power-to-Ammonia-to-Hydrogen chain is quantified with the use of simplified and thermodynamically consistent model, where 1 kg of hydrogen is delivered. Lower heating value basis is 33.3 kWh/kg of H₂. The main focus is shed on establishing the round-trip efficiency of using ammonia as a hydrogen carrier, rather than a specific equipment design.

Each process step follows the same calculation procedure, where key thermodynamic data and typical performance indicators are collected from scientific sources and techno-economic studies. Following, stoichiometric relationships are used to connect one 1 kg of hydrogen basis to the corresponding water, nitrogen and ammonia flows. Multiplication of these flows by literature-based energy values gives the energy use of each process, which in total gives the summing contribution of all steps. Furthermore, the round-trip efficiency is computed as the ratio of hydrogen LHV to total energy use.

4.1 Water Electrolysis

Water electrolysis converts electrical energy into chemical one, which is stored in hydrogen, by splitting water into hydrogen and oxygen. In this thesis, the simplified model of electrolysis is used to distinguish the thermodynamic minimum energy requirement and electricity consumption of large-scale electrolyser system. (Buttler and Spliethoff, 2018) The value of 33.3 kWh/kg for lower heating value (LHV) is used as the reference for chemical energy content (JRC, 2024). Electrolysis overall chemical reaction:



, which underlines fixed relationships between hydrogen and water, where 1 kg of hydrogen corresponds to 500 mol of H₂ and therefore 500 mol of H₂O. Below presented stoichiometry and basic properties:

Table 2. Stoichiometry and basic properties.

Hydrogen LHV	Molar mass of H ₂	Molar mass of H ₂ O	Water per kg of H ₂
E_{LHV,H_2} [kWh/kg]	M_{H_2} [g/mol]	M_{H_2O} [g/mol]	m_{H_2O} [kg/kgH ₂]
33.3	2.0	18.0	9.0

A typical system-level performance efficiencies of a large-scale alkaline and PEM electrolysers were chosen with reported 50 – 60 kWh electricity consumptions, which corresponds to approximately 60 – 70% efficiency on an LHV basis (JRC, 2025). The central value $\eta_{el} = 0.65$ (65%) was chosen and represents the realistic and non-optimistic operating point. Furthermore, the specific electricity consumption of the electrolysis stage is calculated from this formula:

$$E_{el} = \frac{E_{LHV,H_2}}{\eta_{el}} = \frac{33.3}{0.65} = 51.23 \frac{kWh}{kg_{H_2}} \quad (2)$$

Obtained value for electricity demand lies in the middle of the 50 – 60 kWh/kg range, which is reported for commercial and near-commercial plants. Moreover, the electricity demand is further calculated for both high efficiency ($\eta_{el} = 0.70$) and low efficiency ($\eta_{el} = 0.60$) cases and presented below.

Table 3. Calculated electricity demand range.

Low-efficiency	High-efficiency
$E_{el,low}$ [kWh/kg]	$E_{el,high}$ [kWh/kg]
55.50	47.57

4.2 Air Separation Unit

The Air Separation Unit (ASU) plays a significant role in the Power-to-Ammonia chain as it provides high-purity nitrogen for ammonia synthesis by cryogenic distillation of air. This technology is considered as dominant for large-scale nitrogen production, as it can achieve high purity, which is required for the next stage – Haber-Bosch process. (Smith & Klosek, 2001) In this thesis, the ASU is modelled and calculated with single specific electricity consumption, scaled to nitrogen flow required per kilogram of hydrogen delivered. The

demand for nitrogen is linked to the amount of ammonia that stores 1 kilogram of hydrogen and can be presented in following overall reaction:



, where the molar mass of ammonia (17 g/mol) and 1 kg of hydrogen corresponds to roughly 2.83 kg of NH₃ delivered. Using this information, the nitrogen requirements were obtained as follows:

Table 4. Nitrogen demand variables.

Ammonia needed per kg H ₂	Molar mass of NH ₃	Moles of NH ₃	Moles of N ₂	Molar volume at STP	Nitrogen volume per kg H ₂
m_{NH_3}	M_{NH_3}	n_{NH_3}	N_{N_2}	V_m	V_{N_2}
2.83	17	167	83.5	0.0224	1.87

, where nitrogen volume was obtained from:

$$V_{N_2} = n_{N_2} * V_m = 83.5 * 0.0224 \approx 1.87 \text{ Nm}^3 \quad (4)$$

Furthermore, the performance assumptions were made for modern large cryogenic ASU with specific power consumption of 0.3 – 0.45 kWh per Nm³ of high-purity oxygen or nitrogen (Zhang et al., 2014). In this thesis, a central value $e_{ASU} = 0.4$ kWh/Nm³ was adopted for high-purity nitrogen used in ammonia synthesis. Therefore, the ASU electricity consumption per 1 kg of hydrogen is obtained from:

$$E_{ASU} = V_{N_2} * e_{ASU} = 1.87 * 0.4 = 0.75 \frac{kWh}{kg_{H_2}} \quad (5)$$

In addition, the consumption of electricity was also calculated for low ($e_{ASU} = 0.35$) and high ($e_{ASU} = 0.45$) specific consumption rates:

Table 5. Electricity demand range for ASU.

Low-energy	High-energy
$E_{ASU,low}$ [kWh/kg]	$E_{ASU,high}$ [kWh/kg]
0.65	0.84

Low-energy and high-energy values will be used for sensitivity analysis later in this thesis.

4.3 Haber-Bosch Ammonia Synthesis

Large scale ammonia production is derived from the Haber-Bosch process, where ammonia is synthesised from nitrogen and hydrogen over an iron-based catalyst. In the Power-to-Ammonia, hydrogen is supplied by electrolysis and nitrogen by ASU, where the main electrical demand is related to gas compression, circulation in the synthesis loop and auxiliary loop. (Jiang & Feng, 2019)

The stoichiometric relationships described in the previous section (ASU) will be used for required following calculations. For green ammonia plants, the loop electricity consumption is approximated at around 0.8 – 1.2 MWh per tonne of NH₃, once the feedstock production is excluded (Cameli et al., 2024). The synthesis stage is modelled using a single specific electricity consumption $e_{HB} = 1$ MWh/t and therefore is used in following equation:

$$E_{HB} = e_{HB} * m_{NH_3,t} = 1 * 0.00283 = 0.00283 \frac{MWh}{kg} = 2.83 \frac{kWh}{kg_{H_2}} \quad (6)$$

Moreover, the low and high consumption rates are used to calculate the range and retain for sensitivity analysis:

Table 6. Electricity demand range for Haber-Bosch process.

Low-energy	High-energy
$E_{HB,low}$ [kWh/kg]	$E_{HB,high}$ [kWh/kg]
2.26	3.40

4.4 Ammonia Storage and Transportation

In this stage, the ammonia is stored and transported in liquid form to the final destination, where the hydrogen is later recovered. Near ambient or atmospheric pressure and about -33 °C is sufficient to liquify the ammonia and benefit from low boil-off losses and well-established infrastructure (Portarapillo et al., 2025, Wang et al., 2025). The calculations presented in this section follow the same basis as in previous sections, where 1 kg of hydrogen is stored as roughly 2.83 kg of ammonia, according to the previous calculations. The storage and transport energy is expressed as specific terms per tonne of ammonia and

per tonne-kilometre, which corresponds to the literature evidence and highlights that logistics contribute to a small fraction of the total P2A2H energy use. (Portarapillo et al., 2025).

In the calculations, the storage term $e_{stor} = 30 \text{ kWh/t}$ or 0.03 kWh/kg , which is a typical electricity use for refrigeration, pumping and auxiliary in industrial ammonia tanks for a moderate storage period. While the specific energy for transport $e_{transp} = 5 \cdot 10^{-4} \text{ kWh/t}$ or $5 \cdot 10^{-7} \text{ kWh/kg}$, which is derived from estimates of energy demand for bulk ammonia transport by ship. The number is usually below 2 kWh per MWh of ammonia per 100 km, which corresponds to very low energy consumption values when converted to mass and energy basis. (Wang et al., 2025) Calculations of storage and transport energy is presented below:

$$E_{stor} = e_{stor} * m_{NH_3,t} = 0.03 * 2.83 = 0.085 \text{ kWh} \quad (7)$$

$$E_{trans} = e_{trans} * m_{NH_3,t} * D = 5 * 10^{-7} * 2.83 * 500 = 0.0007 \text{ kWh} \quad (8)$$

, where D is the distance and, in our case, the central value of 500 km was chosen, which resulted in following values for energy demand:

Table 7. Electricity demand for storage and transportation.

Storage	Transportation	Total
E_{stor} [kWh/kg]	E_{transp} [kWh/kg]	E_{tot} [kWh/kg]
0.085	0.0007	0.086

Moreover, to assess how distance affects the energy demand associated with transportation, additional values of 0 km, 2000 km and 10 000 km were added and resulted in following:

Table 8. Electricity demand for storage and transportation at different distances.

Distance	Transportation	Storage	Total
D [km]	E_{transp} [kWh/kg]	E_{stor} [kWh/kg]	E_{tot} [kWh/kg]
0	0	0.085	0.085
500	0.0007		0.086
2000	0.0028		0.088
10 000	0.0142		0.099

4.5 Ammonia Cracking

In the final stage, ammonia is decomposed back into nitrogen and hydrogen in a catalytic cracking reactor, typically at 500 – 800 °C and moderate pressures (Chatterjee et al., 2021). The overall cracking reaction is written below:



The same basis of 1 kg delivered hydrogen is used, where 2.83 kg of ammonia should be cracked. Molar quantities presented in the previous sections. From the stoichiometry, 2 ammonia moles result in 3 mols of hydrogen, so

$$n_{H_2cr} = \frac{3}{2} * n_{NH_3} = \frac{3}{2} * 167 \approx 251 \text{ mol} \approx 0.5 \text{ kg} \quad (10)$$

Due to the fact that overall P2A2H basis is defined on 1 kg of hydrogen output, the upstream electrolysis and synthesis stages are sized accordingly so 1 kg of hydrogen can be recovered after cracking and purification losses. This is a simplified version of this process, where we assume full conversion in the cracking reactor and therefore account for purification losses. (Spatolisano et al., 2023)

The reaction is endothermic, so the theoretical minimal heat required is nearly 0.88 MWh/t for cracking 1 tonne of NH₃. In reality, cracking systems need much more energy due to the heat losses, finite heat recovery and imperfect operation. Chatterjee et al. (2021) report that energy demand is within the range 1.17 – 1.76 MWh/t with current technologies. In this thesis, the value of $e_{cr} = 1.5$ MWh/t was taken as the central value within the range. The mass of ammonia to be cracked remained 0.00283 t. The cracking energy per kilogram of hydrogen delivered is calculated using following formula:

$$E_{cr} = e_{cr} * m_{NH_3,t} = 1500 * 0.00283 = 4.25 \frac{kWh}{kg_{H_2}} \quad (11)$$

Therefore, demand with low-energy (1.2 MWh/t) and high-energy (1.8 MWh/t) consumption factors were calculated using equation 11 and presented below:

Table 9. Cracking energy range per kilogram of hydrogen delivered.

Low-energy	High-energy
$E_{cr,low}$ [kWh/kg H ₂]	$E_{cr,high}$ [kWh/kg H ₂]
3.40	5.09

4.6 Hydrogen Purification

The product gas after cracking contains mainly hydrogen and nitrogen with little traces of ammonia and other impurities. Therefore, it should be purified to meet fuel-cell grade specifications, which is $>99.97\%$ H_2 . (Chen et al., 2022) A pressure swing adsorption (PSA) is assumed to perform a hydrogen purification, which is the most widely used industrial technology for high-purity hydrogen production due to the low energy demand and high achievable purity. (Rumbo Morales et al., 2022)

The calculations are based on 1 kg of purified hydrogen delivered as in previous sections. Moreover, hydrogen recovery and specific electricity consumption are two key parameters to represent PSA performance at system level. Reported recoveries are roughly 85 – 90% at purities above 99.97%, so the representative value of $R_{H_2} = 90\%$ was chosen for hydrogen recovery for PSA systems (Chen et al., 2022). Furthermore, according to Rumbo Morales et al. (2022) the range for electricity consumption is 0.25 – 0.35 kWh/kg, so the value of $e_{PSA} = 0.3$ kWh per kilogram of hydrogen product. The calculation of hydrogen feed was performed as follows:

$$m_{H_2,feed} = \frac{m_{H_2,out}}{R_{H_2}} = \frac{1}{0.9} \approx 1.11 \text{ kg} \quad (12)$$

The electricity consumption of the PSA unit is calculated using this formula:

$$E_{PSA} = e_{PSA} * m_{H_2,out} = 0.3 * 1 = 0.3 \frac{kWh}{kg_{H_2}} \quad (13)$$

Sensitivity case using the reported range is presented in the table below:

Table 10. Sensitivity case for PSA.

Low-energy	High-energy
$E_{PSA,low}$ [kWh/kg H_2]	$E_{PSA,high}$ [kWh/kg H_2]
0.25	0.35

5 Results

This section combines the results from previous stages and highlights the total electricity input required per 1 kg of delivered hydrogen in the P2A2H cycle. Moreover, it indicates the round-trip efficiency on an LHV basis. Table 11 shows the consumption of each process step:

Table 11. Electricity consumption at each stage.

Water electrolysis	Air Separation Unit	Haber-Bosch synthesis	Ammonia storage and transportation	Ammonia cracking	Hydrogen purification (PSA)
E_{el} [kWh/kg]	E_{ASU} [kWh/kg]	E_{HB} [kWh/kg]	$E_{stor+transp}$ [kWh/kg]	E_{cr} [kWh/kg]	E_{PSA} [kWh/kg]
51.23	0.75	2.83	0.09	4.25	0.30

The total electricity demand per kilogram of hydrogen is calculated by summing the contribution of all stages:

$$\begin{aligned}
 E_{tot} &= E_{el} + E_{ASU} + E_{HB} + E_{stor+transp} + E_{cr} + E_{PSA} = \\
 &= 51.23 + 0.75 + 2.83 + 0.09 + 4.25 + 0.3 = 59.45 \frac{kWh}{kg_{H_2}}
 \end{aligned} \tag{14}$$

The total number represents the electrical energy, which must be supplied to the combination of all stages in order to get 1 kg of hydrogen at the specific purity. On the other hand, the round-trip efficiency of the P2A2H cycle can be described as the ratio between chemical energy content of the final hydrogen and the total electricity input:

$$\eta_{P2A2H} = \frac{E_{LHV,H_2}}{E_{tot}} = \frac{33.3}{59.45} \approx 0.56 \text{ or } 56\% \tag{15}$$

For simple sensitivity estimation, values of low and high energy were obtained for each stage. The calculation presented below:

$$E_{tot,low} = 47.57 + 0.65 + 2.26 + 0.09 + 3.40 + 0.25 = 54.22 \text{ kWh/kg}_{H_2} \tag{16}$$

and the round-trip efficiency:

$$\eta_{P2A2H} = \frac{33.3}{54.22} \approx 0.61 \text{ or } 61\% \quad (17)$$

The worst-case scenario includes high-electricity consumption and less performance at each stage, presented below:

$$E_{tot,high} = 55.5 + 0.84 + 3.4 + 0.09 + 5.09 + 0.35 = 65.27 \text{ kWh/kg}_{H_2} \quad (18)$$

, resulting in lower round-trip efficiency:

$$\eta_{P2A2H} = \frac{33.3}{65.27} \approx 0.51 \text{ or } 51\% \quad (19)$$

The resulting round-trip efficiency range is roughly 51 – 61% on an LHV basis, which is consistent with assessments of green ammonia and hydrogen energy chains. In cases, where hydrogen is considered as the final output rather than electricity generation from hydrogen. (Portarapillo et al., 2025; Jian & Feng, 2019)

Figure 4 shows the total electrical energy distribution required to deliver one kilogram of hydrogen, where the largest share is consumed during the water electrolysis stage. The remaining 8.22 kWh/kg is distributed between the auxiliary processes such as: nitrogen production in air separation unit (0.75 kWh/kg), Haber-Bosch synthesis loop (2.83 kWh/kg), ammonia storage and transport (0.09 kWh/kg), ammonia cracking (4.25 kWh/kg) and hydrogen purification (0.3 kWh/kg).

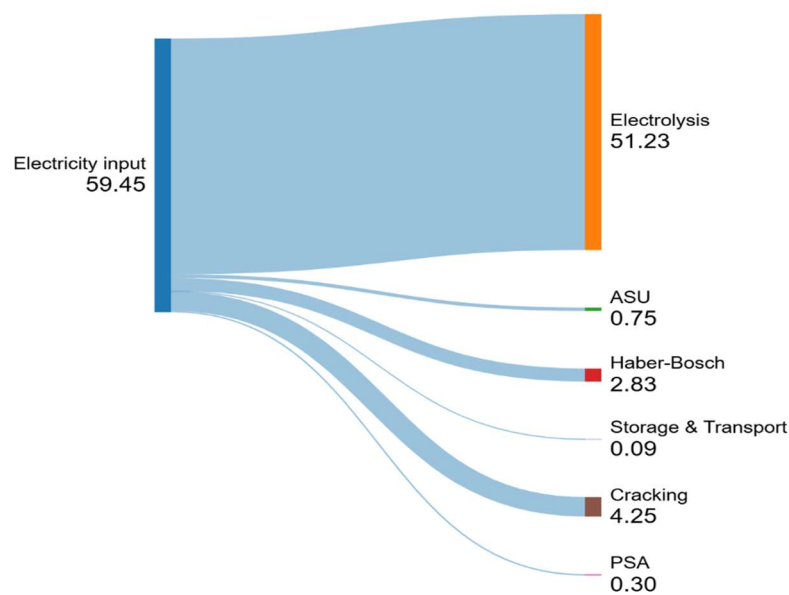


Figure 4. Distribution of total electrical energy in kWh/kg among the unit operations.

The chosen LHV value of 33.3 kWh/kg as a reference for useful chemical energy, corresponds to the overall Power-to-Ammonia-to-Hydrogen round-trip efficiency of 56%, which was obtained as the ratio between LHV and specific electricity input. Furthermore, Figure 5 presents the difference in round-trip efficiency for three use cases: a base case (56%) using central values, an optimistic case (61%) with the highest efficiencies and lowest specific energy consumption factors, and a conservative case (51%) with the least efficient values for the whole chain.

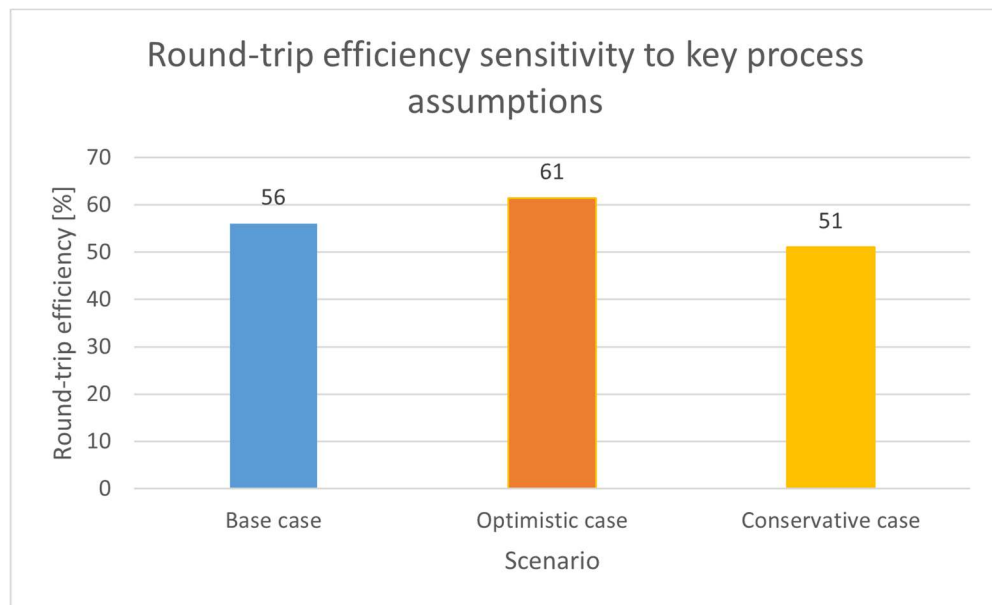


Figure 5. Round-trip efficiency sensitivity.

The results indicate that realistic technology improvements can possibly shift the P2A2H round-trip efficiency from the conservative 51% scenario up to 61%, while the base case remains around 56%. Such 10-percentage point span highlights the strong influence of electrolyser and cracking performance on overall system efficiency.

In addition, the Table 8, presented in the previous section, highlights how increasing distance slightly affects electrical energy demand and round-trip efficiency at the transportation and storage stage. Figure 6 illustrates this trend by showing a small increase in total electrical demand and a corresponding reduction in round-trip efficiency with longer distances, confirming that transport distance has only a minor impact on the overall performance of the system, within the analysed range.

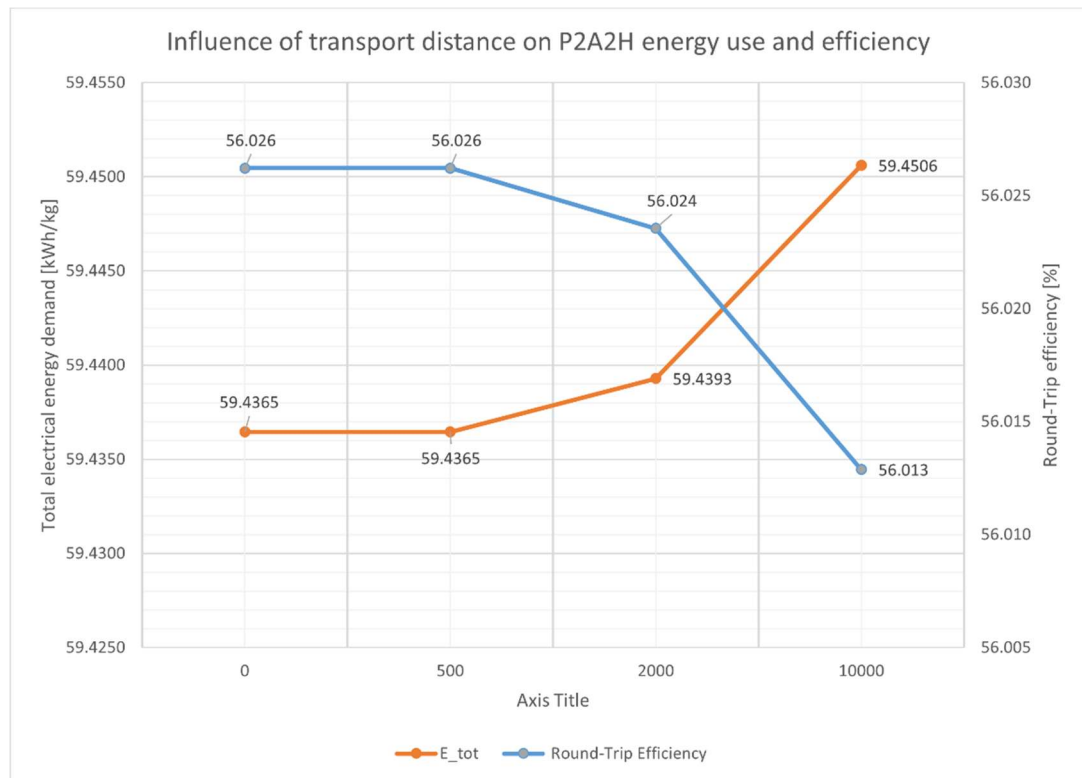


Figure 6. Effect of transport distance on total electricity demand and round-trip efficiency.

From Figure 6, it is clearly visible that increasing distance results in higher energy demand and reduced round-trip efficiency. Nevertheless, even the longest distance of 10 000 km result in only a 0.013 % difference in the round-trip efficiency with additional 0.0142 kWh/kg of H₂.

6 Discussion

The obtained results indicate that the consumption of the Power-to-Ammonia-to-Hydrogen chain is 59.45 kWh per 1 kg of hydrogen, which corresponds to a round-trip efficiency of 56% on an LHV basis. A simplified model was used to capture main characteristics of current P2A2H concepts and fall within the reported range of 50 – 60% efficiency, where hydrogen is taken as the final output (Giddey et al., 2017). The results highlight that electrolysis and ammonia cracking are the most energy demanding stages and dominate the overall consumption, while air separation unit, Haber-Bosch loop, storage and transportation, and hydrogen purification require significantly less energy.

6.1 Sensitivity analysis

The sensitivity analysis presents noticeable variations in electrolyser and cracking performance and therefore impact on the round-trip efficiency. For instance, when the electrolysis efficiency is increased from 60% to 70% and specific cracking energy is reduced to 1.2 MWh/t_{NH₃}, the total electricity consumption decreases to 54.22 kWh/kg down from 65.27 kWh/kg. This results in the round-trip efficiency of 61 %, which is 10% more than our central value. The increased performance of the whole system indicates the importance of technological improvements in these two steps, which can result in improved efficiency by roughly ± 5 percentage points (Buttler & Spliethoff, 2018).

Furthermore, the combination of both the ASU and Haber-Bosch loop electricity consumption variation, suggested by literature, resulted only in a minor influence on the overall results. Even with the highest energy consumption cases, both stages together resulted in less than 7% of total energy consumption, because feedstock generation is already accounted for in the electrolysis stage (Cameli et al., 2024). Similarly, the transport distance variations showed small influence on the overall efficiency, even 10 000 km distance resulted in 0.013% difference from the central case with 500 km. This finding supports previous reports, which stated the dominance of conversion losses rather than logistics energy, especially with existing ammonia infrastructure (Portarapillo et al., 2025).

6.2 Limitations

The analysis remains subject to several limitations, which should be considered in interpreting the results. This report used a simplified model with a specific energy consumption and a simple efficiency range, without detailed modelling of operating pressure, temperature, part load-behaviour and dynamic interaction. However, real performance of electrolysers, air separation units, Haber-Bosch loops and ammonia cracking units is strictly dependent on operating conditions and capabilities, which might have a huge impact on the overall performance (Buttler & Spliethoff, 2018). Moreover, the full ammonia conversion was assumed during the cracking and purification stages, which resulted in slightly higher efficiency and should have added minor energy penalties throughout the stages (Chen et al., 2022).

Finally, the study was made solely on energy efficiency and, therefore, neglects capital and operating costs or environmental impacts such as greenhouse emissions and NO_x formation during combustion. Techno-economic and life-cycle assessments from the literature indicate that round-trip efficiency is not the only factor influencing the competitiveness of ammonia to alternative hydrogen carriers, but also plant investments, fuel prices and regulatory frameworks (Giddey et al., 2017). Boundary conditions are defined for steady-state operating point with 1 kg of hydrogen delivered and, therefore, neglect aspects such as part-load operations, seasonal storage sizing and integration with power systems.

7 Conclusions

In this thesis the energy performance of a Power-to-Ammonia-to-Hydrogen chain is quantified using a consistent model, which is based on 1 kg of hydrogen delivered. The central results indicate the round-trip efficiency of approximately 56% with electricity consumption of 59.45 kWh/kg of H₂ on a LHV basis. The overall efficiency lies within the range of 50 – 60%, reported in the recent assessments of green ammonia and hydrogen chains, where hydrogen is taken as the final output rather than electricity generation source.

Stage analysis revealed that water electrolysis is by far the most dominant source of energy consumption, which requires 51.23 kWh/kg of H₂. It is followed by stages such as the air separation unit, Haber-Bosch synthesis loop, storage and transport, and hydrogen purification, which together account for only 8 kWh/kg of H₂, indicating the significance of conversion losses on overall performance of P2A2H, rather than logistics. Moreover, the sensitivity calculations reveal the possibility of improving round-trip efficiency up to 61% due to realistic improvements in electrolyser efficiency and reduction in ammonia cracking demand.

The analysis on different transport distances underlines the insignificant impact on the overall chain efficiency, where even 10 000 km distance result in an additional 0.014 kWh/kg of H₂ comparing to central values (500 km distance) and assuming same specific energy values. This result supports the studies on ammonia suitability for long-distance renewable hydrogen transport with major energy penalties coming from conversion processes.

Furthermore, the greatest potential for round-trip efficiency improvements is coming from electrolyser and ammonia cracking stages, while the impact of transport distance and auxiliary units remains comparatively limited. Considering assumptions and limitations presented in this thesis, the Power-to-Ammonia-to-Hydrogen pathway can be characterized as a medium efficiency and logistically favourable option for hydrogen storage and transport, which provides useful benchmark for future comparison of technological development and hydrogen carriers concepts.

The analysis also demonstrates that the P2A2H is no longer purely theoretical. Projects such as NEOM Green Hydrogen Project in Saudi Arabia, the H2Global Fertiglobe supply chain from Egypt to Rotterdam and Project Yuri in Western Australia indicate that the full P2A2H chain is technically and commercially realisable at industrial scale. The efficiency characteristics identified in this thesis are directly applicable to each of these projects, outlining the dominance of electrolysis and cracking stages.

Future improvements in electrolyser efficiency beyond 70% LHV and reductions in ammonia cracking energy demand below 1.2 MWh/t of NH₃ represent the most impactful development areas, where solid oxide electrolysis and novel low-temperature cracking catalysts as the most promising directions.

The competitiveness of the P2A2H pathways does not solely rely on energy efficiency alone. Techno-economic factors such as electrolyser capital costs, renewable electricity prices and hydrogen regulations combined affect whether green ammonia is cost-effective compared to alternatives, such as pipeline hydrogen or LOHCs. Future work is required to complement this analysis with missing techno-economic and lifecycle assessments, which will provide a more complete picture of the P2A2H chain's role in the global hydrogen economy.

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