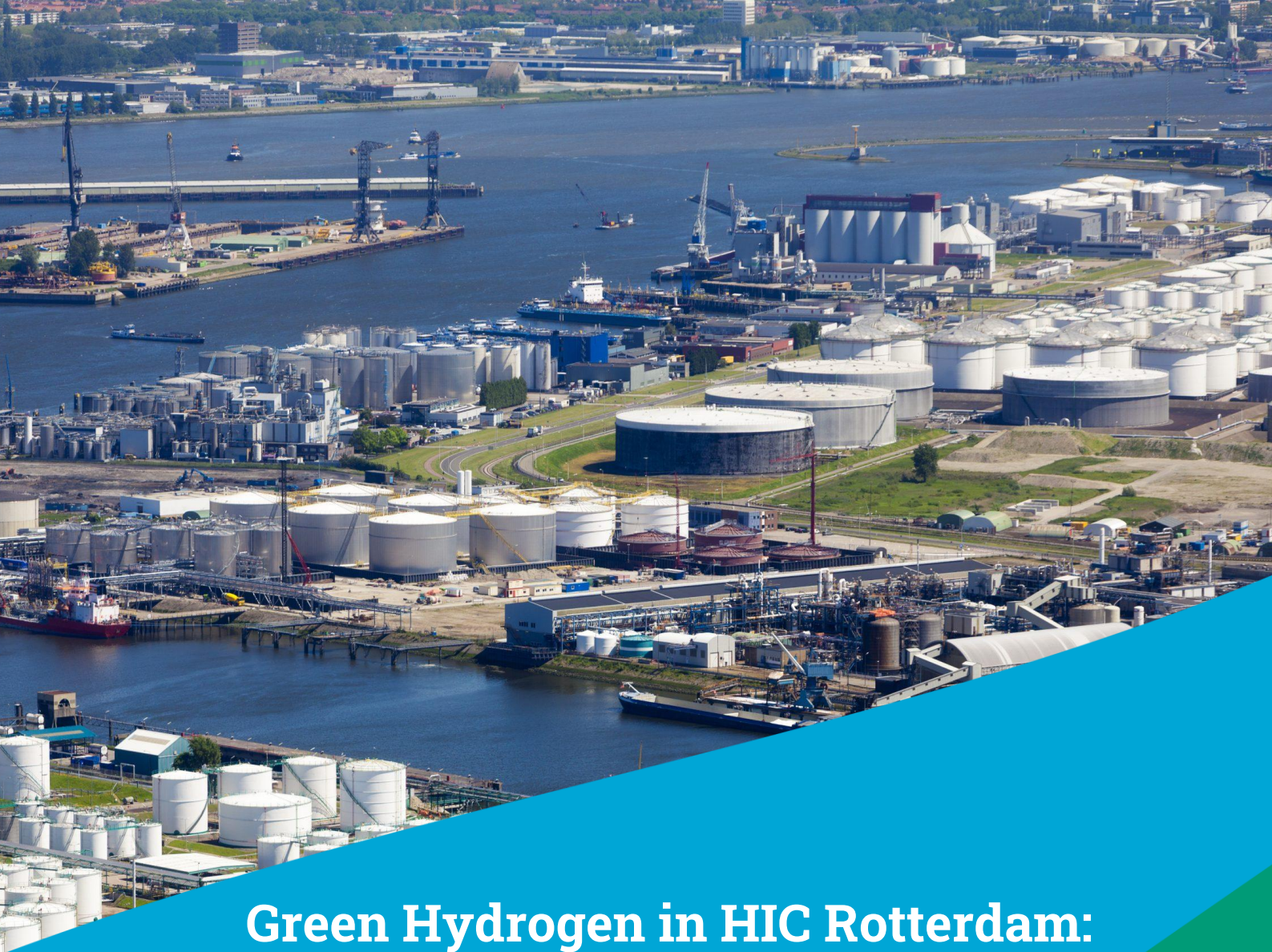




Green Hydrogen in HIC Rotterdam: Enabling Competitive Domestic Production vs. Imports

A Techno-Economic Modelling (Linny-R) Approach

MSc Thesis Complex Systems Engineering and Management
Gijs Kuijl

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by

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Acknowledgment

In front of you lies my master thesis: *“Green Hydrogen in HIC Rotterdam: Enabling Competitive Domestic Production vs. Imports”*, which I have worked on intensively over the past six months. This thesis has been written as final part of my Master of Science in Complex Systems Engineering and Management at the Faculty of Technology, Policy, and Management at TU Delft. With the completion of this thesis, I am also marking the end of my life as a student.

Although at times it felt like this thesis had completely taken over my life, looking back, I can confidently say it was one of the most intense and rewarding periods of my academic journey. Reflecting on this journey, I am very proud of the personal growth I have experienced. Early on, I went through the frustrating experience of repeating a year of high school. Only later did I realize that it had taught me the value of hard work and perseverance in achieving my goals. This lesson shaped the rest of my academic path: from completing HAVO to finishing VWO, and eventually pursuing my Bachelor’s and Master’s studies in Delft, where excellence often feels like the standard. In this environment, I learned to work diligently and stay focused on long-term goals. I can proudly say that my perseverance has truly paid off, and I am very grateful for the experience and the support I have received throughout this process.

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*Gijs Kuijl
Delft, August 2025*

Executive Summary

Problem Statement and Research Question

The Netherlands targets a climate-neutral energy system by 2050, with offshore wind electricity and green hydrogen as key pillars. As an emerging “hydrogen hub”, the Port of Rotterdam is central to this transition. However, domestic hydrogen production in this area is currently economically challenging, while importing hydrogen—mainly via ammonia—is often cheaper but increases dependence on foreign supply. This study therefore addresses the question:

“Under which techno-economic and strategic conditions is onshore hydrogen production, powered by offshore wind, cost-competitive with ammonia-based hydrogen imports, while contributing to a robust hydrogen and electricity system in the Port of Rotterdam?”

Knowledge Gap

Although there is a growing academic interest in hydrogen systems, existing studies rarely address the Dutch context, particularly the Port of Rotterdam. Most comparative analyses focus on other regions and overlook the distinctive characteristics of Rotterdam’s Harbour Industrial Cluster, such as large-scale offshore-wind integration, infrastructure constraints, and concentrated industrial demand. Moreover, few studies assess the dynamic trade-offs between domestic production and hydrogen imports under realistic system conditions. This study addresses that gap using location-specific, scenario-based modelling.

Methodology Overview

To answer the research question and address the identified knowledge gap, an interconnected electricity–hydrogen system model for the Harbour Industrial Cluster Rotterdam was developed in Linny-R—a mixed integer linear programming tool designed for simulating complex energy system dynamics. The study follows an exploratory modelling and analysis approach, using the XLRM framework to structure exogenous uncertainties and policy levers, and evaluates outcomes against the four A’s of energy security: availability, accessibility, acceptability, and affordability. A set of over 400 scenarios were run to test the system under a range of techno-economic conditions.

Key Insights

1. Cost-Competitiveness

Domestic production is only competitive under favourable combinations of power purchase agreement prices, reduced electrolyser capital costs, and moderately high import prices. Competitiveness hinges on the interaction between these three parameters: if one becomes unfavourable, the others must improve significantly to compensate. However, electricity price volatility can undermine hydrogen output, as electrolyzers may shift to reselling power purchase agreement electricity when arbitrage is more profitable than production.

2. System Robustness

System reliability is more constrained by electricity availability than by hydrogen availability, due to the (modelled) flexibility of imports. High grid supply capacity, substantial short-term electricity storage, and stable electricity prices are critical for maintaining steady hydrogen production. Robust performance only occurs when all these enabling conditions are met simultaneously.

3. Strategic Value

Even when imports are cheaper, maintaining domestic production capacity strengthens energy security, reduces dependency, and supports industrial resilience. A balanced mix of domestic capacity and imports offers the most robust pathway under uncertainty, with domestic production able to act as a ‘strategic buffer’ against import supply disruptions, price shocks, or geopolitical risks.

Conclusions

Onshore hydrogen production from offshore wind can be cost-competitive with imports in the Port of Rotterdam only when favourable power purchase agreement prices, reduced electrolyser capital costs, and adequate infrastructure—particularly grid and storage capacity—are in place. Beyond costs, it can play a strategic role in securing supply, stabilising the energy system, and fostering industrial development. A balanced mix of domestic production and imports offers the most resilient pathway under uncertainty.

Actionable Recommendations

Port of Rotterdam Authority

- Maintain a baseline level of domestic hydrogen production capacity which can act as a ‘strategic buffer’ against geopolitical, market, or supply disruptions.
- Accelerate investment in critical infrastructure, including high-voltage grid capacity and large-scale electricity storage to enable stable integration of domestic hydrogen production.
- Coordinate infrastructure planning closely with TenneT, distribution system operators, and storage developers to align timelines and optimise system integration.

Industry

- **Hydrogen producers:** Develop coordinated strategies to reduce electrolyses capital costs, lower power purchase agreement prices, and track global hydrogen import price trends to improve competitiveness. Balance operational flexibility with reliable offtake agreements; avoid excessive power purchase agreement electricity trading that undermines hydrogen supply stability.
- **Hydrogen importers:** Diversify import sources and maintain contingency plans to mitigate supply chain and geopolitical risks.
- **Hydrogen consumers:** Combine spot market purchasing with long-term domestic supply contracts to protect against price volatility and supply disruptions.

Policymakers

- Design policies that balance economic competitiveness with strategic benefits, ensuring domestic production capacity is preserved even when imports are cheaper.
- Use a holistic system approach that integrates electricity and hydrogen market reforms with infrastructure investment, rather than isolated measures.
- Position the Port of Rotterdam as a European ‘blueprint’ for interconnected energy systems, and support demonstration projects that combine domestic production with imports to strengthen resilience.

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Nomenclature

Abbreviations

Abbreviation	Definition
AWE	Alkaline Water Electrolysis
ATR	Afname Tarief Regeling
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CDG	Connected Deep Green
CES	Cluster Energie Strategie
CITr	Corporate Income Tax rate
CO ₂	Carbon Dioxide
DA	Day-Ahead (electricity market)
EMA	Exploratory Modelling and Analysis
EENS	Expected Energy Not Supplied
ENTSO-E	European Network of Transmission System Operators for Electricity
EU	European Union
FLH	Full Load Hours
Gton	Gigatonne
GW	Gigawatt
GWe	Gigawatt electrical
GWhe	Gigawatt-hours electrical
H ₂	Hydrogen
HIC	Haven Industrieel Complex / Harbour Industrial Cluster
HHV	Higher Heating Value
HV	High Voltage
LCOH	Levelized Cost of Hydrogen
LH ₂	Liquid Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LOLE	Loss of Load Expectation
MLP	Multi-Level Perspective
MILP	Mixed-Integer Linear Programming
Mton	Million tonnes
MW	Megawatt
MWe	Megawatt electrical
NPE	Nationaal Plan Energiesysteem
NPVI	Nationaal Programma Verduurzaming Industrie
NH ₃	Ammonia
NO _x	Nitrogen Oxides
O&M	Operations and Maintenance
OPEX	Operational Expenditure
OSW	Offshore Wind
PEH	Programma Energiehoofdstructuur
PEM	Proton Exchange Membrane
PPA	Power Purchase Agreement
RED	Renewable Energy Directive
REPowerEU	Renewable Energy Plan for the EU
RFNBO	Renewable Fuels of Non-Biological Origin
SDE++	Stimulerend Duurzame Energieproductie en Klimaattransitie
SOEC	Solid Oxide Electrolysis Cell
SQ	Sub-Question
TWh	Terawatt-hour
TRL	Technology Readiness Level
UCC	Unit Capital Expenditure
VAWOZ	Verkenning Aanlanding Wind op Zee
VoLL	Value of Lost Load
WACC	Weighted Average Cost of Capital
XLRM	Framework for exogenous uncertainties, levers, relationships, metrics

Symbols

Symbol	Definition	Unit
%	Percentage	%
°C	Degrees Celsius	°C
€	Euro	€
Avg. CO ₂	Average CO ₂ intensity of energy	tCO ₂ /GWh
Avg. SC	Average system costs	M€/GWh
EENS	Expected Energy Not Served	GWh/year
factor (0–1)	Dimensionless factor	–
FLH	Full Load Hours	h/year
GWe	Gigawatt electrical	GWe
GW H ₂ (HHV)	Gigawatt hydrogen – Higher Heating Value	GW
GWhe	Gigawatt-hours electrical	GWhe
GWh H ₂ (HHV)	Gigawatt-hours hydrogen – Higher Heating Value	GWh
H ₂ –E Share	Share of hydrogen production from electrolysis relative to total hydrogen supply	–
kg	Kilogram	kg
kWe	Kilowatt electrical	kWe
LCOH _{electrolysis}	Levelized Cost of Hydrogen (electrolysis)	€/kg H ₂
LCOH _{import}	Levelized Cost of Hydrogen (import)	€/kg H ₂
LCOH difference	Levelized Cost of Hydrogen between electrolysis and import	€/kg H ₂
LOLE	Loss of Load Expectation	h/year
M€	Million euros	M€
M€/GWe/year	Million euros per gigawatt electrical per year	M€/GWe/year
M€/GW H ₂ /year	Million euros per gigawatt hydrogen per year	M€/GW H ₂ /year
MWhe	Megawatt-hour electrical	MWhe
MW	Megawatt	MW
MWe	Megawatt electrical	MWe
SC	System Costs	M€/GWh
tCO ₂ /GWhe	Tonnes CO ₂ per gigawatt-hour electrical	tCO ₂ /GWhe
tCO ₂ /GWh H ₂	Tonnes CO ₂ per gigawatt-hour hydrogen	tCO ₂ /GWh H ₂
TWh	Terawatt-hour	TWh
TWh H ₂	Terawatt-hours of hydrogen	TWh H ₂
VoLL	Value of Lost Load – electricity/hydrogen	M€/GWh

Conversion & Constants

Constant	Value	Unit
Energy content H ₂ (HHV)	39.32	kWh/kg H ₂
Mass equivalent of 1 kWh HHV H ₂	0.025	kg H ₂ /kWh
Electricity-to-hydrogen efficiency (HHV)	0.7021	GWh H ₂ /GWhe

1 Introduction

1.1 Background and Societal Relevance

The transition to a climate-neutral energy system is one of the greatest challenges of this century. It is central to both international and national policy goals, such as the Paris Agreement [1] and the Dutch Climate Accord [2]. The Netherlands aims to reduce greenhouse gas emissions by 55% by 2030 compared to 1990, and to achieve a climate-neutral energy supply by 2050. At the same time, geopolitical shifts, such as Russia's invasion of Ukraine and the re-election of Trump, have underlined the urgency of reducing dependence on foreign energy imports [3]. As outlined in the Nationaal Plan Energiesysteem (NPE) [4] and aligned with the REPowerEU Plan [5], increasing Dutch energy autonomy through electrification and hydrogen is essential for both security of supply and decarbonisation.

An important strategy for increasing Dutch energy autonomy is the large-scale expansion of offshore wind generation capacity. According to studies by the Dutch government [6], [7], installed offshore wind capacity is set to grow from 4.5 GW in 2024 to 21 GW by 2032—covering approximately 75% of current electricity demand, and further expand to 70 GW by 2050, with a significant share dedicated to hydrogen production. To accommodate this growing offshore wind capacity, multiple landing sites are being evaluated as part of the Verkenning/Verbindend Aanlanding Wind Op Zee (VAWOZ) programme [8], [9], [10]. Among them, the Maasvlakte in the Port of Rotterdam—Europe's largest seaport and industrial cluster—plays a crucial role. By 2030, about a third (7.4 GW) of offshore wind capacity is planned to come ashore at the Haven Industrieel Complex (HIC) Rotterdam [11], responsible for 19% of national CO₂ emissions in 2023 [12]. However, integrating this wind energy presents two challenges: matching intermittent supply to demand and minimizing grid congestion, as grid expansion is spatially constrained, economically costly, and time-consuming [6].

Multiple studies [13], [14], [15] suggest that domestic electrolysis could be a promising solution for dealing with grid congestion and enabling large-scale green hydrogen production. Moreover, with its industrial demand and existing power plants, this would allow Harbour Industrial Cluster (HIC) Rotterdam to act as a flexible energy hub by dynamically switching between electricity consumption and generation to integrate wind electricity [11].

1.2 Problem Definition

Despite the potential of domestic electrolysis, economic feasibility remains a significant barrier. As highlighted by [16], hydrogen production via electrolysis in regions such as the Port of Rotterdam is currently not cost-competitive compared to hydrogen imports from regions with abundant and low-cost renewable energy resources. Regions such as Australia, Morocco, Chile, the United States, Norway, and the Middle East can produce hydrogen more affordably due to economies of scale and lower land use [17], [18], [19]. This is illustrated in Figure 1-1, which shows the estimated cost ranges for green hydrogen production. For example, Chile, Morocco, and the Arabian Gulf could achieve production costs of under 2.0 USD/kg H₂, compared to the North Sea's 3.5–4.0 USD/kg H₂ range¹.

As a result, countries like the Netherlands currently face limited market incentives to scale up domestic electrolysis due to the higher production costs of green hydrogen. Instead, they risk growing dependence on hydrogen imports, a vulnerability that becomes more critical in times of geopolitical uncertainties. This raises a key question: Under what techno-economic conditions can offshore wind-based hydrogen compete with imports, and what strategic interventions are needed to support this shift?

¹ Note: Reference [17] reports values in USD (2018). For comparison, 1 USD (2018) $\approx$ 1.16 EUR (2025), accounting for inflation and exchange rate adjustments.

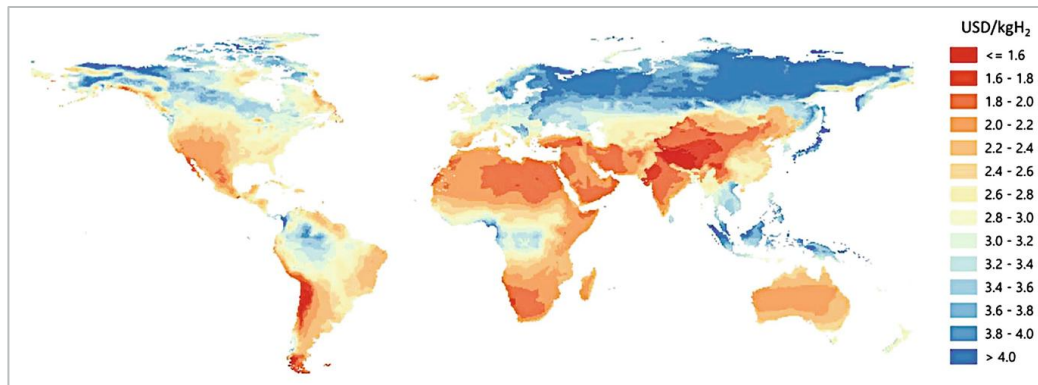


Figure 1-1: Indicative long-term hydrogen production costs (adapted from [17])

With its central role in offshore wind integration, hydrogen infrastructure, and industrial demand, HIC Rotterdam is a critical hub for Europe’s energy transition. However, the long-term viability and cost-competitiveness of large-scale domestic hydrogen production relative to imports remain uncertain, particularly under evolving market, policy, and infrastructure constraints. This thesis assesses the techno-economic trade-offs between domestic electrolysis and hydrogen imports and explores strategic interventions to enhance a robust and cost-effective hydrogen supply in the Port of Rotterdam.

1.3 Alignment to MSc Complex Systems Engineering and Management

As can be seen in the mission statement of the Port of Rotterdam Authority [20]—“*The Port of Rotterdam Authority creates economic and social value by achieving sustainable growth in a world-class port in collaboration with clients and stakeholders.*”—this thesis is aligned with the broader mission of the Port of Rotterdam. At the same time, it also aligns with the objectives of the MSc Complex Systems Engineering and Management (CoSEM) programme at TU Delft. It applies a systems approach to integrating offshore wind electricity and large-scale hydrogen production at HIC Rotterdam, a complex socio-technical system where technological, economic, and regulatory factors interact. It builds on key CoSEM courses, including Complex Systems Engineering (SEN112), which introduces systems thinking in socio-technical environments, CoSEM Research Challenges (SEN131B), which focuses on literature research methodology, and the energy track courses, particularly Design of Integrated Energy Systems (SEN1531), which focuses on energy system modelling and optimisation.

By involving industry and policy insights, this research bridges the gap between technological feasibility and policy development, thereby improving the economic viability of energy systems. It provides both academic and practical insights into the role of hydrogen in offshore wind electricity integration and contributes to discussions on sustainable energy development in industrial regions such as the Port of Rotterdam.

1.4 Report Structure

Following this introduction, Chapter 2 provides the theoretical background, introducing key concepts relevant to the study. It concludes with the formulation of the research questions that guide the remainder of the report. Chapter 3 then outlines the research methodology, detailing the modelling approach as well as the evaluation framework used to assess both technical and economic outcomes. Next, Chapter 4 elaborates on the model conceptualisation and specification, laying the foundation for its practical application. Building on this, Chapter 5 describes the model's implementation in Linny-R, highlighting the key research components. Subsequently, Chapter 6 presents the experimental setup and the corresponding results across different scenario types, providing a basis for comparison and analysis. Chapter 7 follows with a discussion of the findings, interpreting the results in the context of existing literature and identifying key limitations as well as insights. Thereafter, Chapter 8 brings the study to a conclusion, offering both scientific as strategic recommendations and suggestions for future research. Finally, Chapter 9 provides a reflection on the research process and outcomes, considering methodological choices, challenges, and lessons learned. To support the main text, the appendices include supplementary materials such as the literature review, data sources, and the complete set of results.

2 Theoretical Background

This chapter provides the theoretical foundation for this study. It synthesises key insights from both scientific and grey literature on hydrogen supply chains, offshore wind integration, and the strategic role of the Port of Rotterdam. Section 2.1 outlines the literature review methodology, while Section 2.2 and Section 2.3 present and conclude the main findings across technical, economic, and policy domains. Finally, Section 2.4 identifies relevant knowledge gaps, which lead to the sub and main-research questions of this thesis.

2.1 Methodology of Literature Review

To identify the academic knowledge gap, a comprehensive search and analysis of scientific and grey literature was conducted. For scientific literature, this involved developing a structured search strategy, selecting relevant studies, and synthesising the findings. For grey literature, desk research was combined with expert consultations within the Port of Rotterdam to gather policy reports, industry studies, and strategic documents relevant to this thesis. Insights from both scientific and grey literature were analysed to identify areas requiring further research. A detailed overview of the search strategy, selection process, selected literature, and synthesis of literature—including both scientific and grey sources—is provided in Appendix A. Section 2.2 and 2.3 present the main findings and conclusions, while Section 2.4 summarises the identified research gaps and their implications for this thesis.

2.2 Findings of Literature Review

2.2.1 Core System Components

Haven Industrieel Complex (HIC) Rotterdam

Haven Industrieel Complex (HIC) Rotterdam is part of the Rotterdam-Moerdijk industrial cluster, the largest in the Netherlands, and an important gateway for energy and raw materials entering the country. These raw materials are processed into fuels, plastics, building materials, and other essential products. The cluster is home to more than 3,000 companies and handles an annual throughput of 455 million tonnes of goods. In the Netherlands, the cluster supports 200,000 jobs and generates over €30 billion in added value [11].

As a strategic hub for Northwest Europe, HIC Rotterdam is also important for energy imports and global trade. In 2021, about 1,900 TWh of energy carriers arrived in the Port of Rotterdam, representing around 12% of Europe's total energy supply and more than double the Dutch domestic energy consumption [21]. Approximately 96% of this incoming energy was fossil-based, consisting mainly of crude oil, oil products, liquefied natural gas (LNG), and coal. Of this amount, around 34% is processed within HIC Rotterdam, 6% is used for bunkering in the port, and the remaining 60% is transported into the hinterland, which includes other regions in the Netherlands, Germany, Belgium, and even Northern France .

Currently, the industrial in HIC is primarily focused on petroleum refining and the chemical sector, making it the 3rd largest oil refining hub in Europe [3], [22]. These operations result in substantial greenhouse gas emissions, with HIC accounting for 19% of total Dutch CO₂ emissions in 2023 [12]. In 2021, these emissions were evenly distributed across refining, chemical production, and electricity generation, which was primarily fuelled by coal and natural gas [21].

Looking ahead, HIC anticipates a shift in the energy mix, with a growing share of biological fuels and green hydrogen derivatives expected to arrive. As described in the introduction, the energy intensity of HIC makes it a suitable region to integrate large-scale offshore wind electricity and thereby green hydrogen production through electrolysis. Moreover, the cluster is expected to serve as an important entry point for hydrogen imports, strengthening its role in the future European energy landscape [23].

Offshore Wind Electricity and Landfall

Offshore wind electricity refers to electricity generated by wind turbines installed in oceans or lakes. It is increasingly being developed due to space limitations and dense populations in coastal areas. Offshore wind has several advantages—including a large available area, high wind speeds, low turbulence, and proximity to cities—making it a promising renewable energy source. However, challenges include higher costs, difficult operating conditions, and limited accessibility. Offshore wind electricity is particularly attractive due to the stronger and more consistent winds, resulting in higher electricity production compared to onshore wind [24].

Additionally, offshore wind electricity provides a renewable feedstock for green hydrogen production through electrolysis, which can occur domestically at HIC Rotterdam or in regions with abundant renewable energy for export. This allows HIC Rotterdam to serve as both a production hub and an import gateway, facilitating the integration of green hydrogen into the national and European energy system.

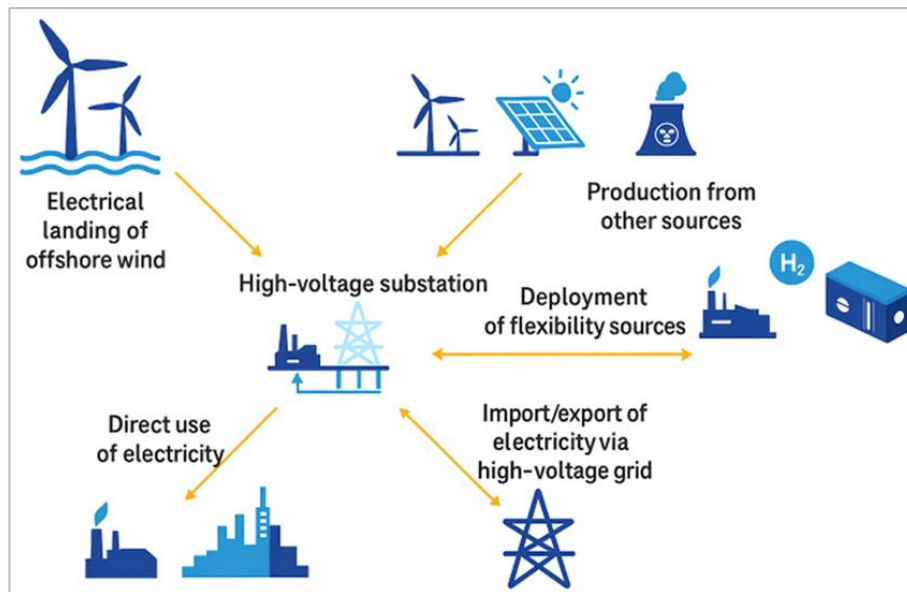


Figure 2-1: Illustration of energy flows for electrical landing at a coastal substation (adapted from [25])

Figure 2-1 provides an overview of the energy flows associated with the electrical landfall of offshore wind at coastal substations, adapted from [25]. Electricity from offshore wind farms and other generation sources (e.g., solar, nuclear, biomass) is transmitted to an onshore high-voltage substation. From there, electricity can be used directly by industrial consumers, or directed to flexible sources such as Battery Energy Storage Systems (BESS) or electrolyzers for green hydrogen production. Additionally, electricity can be imported or exported via the national grid to manage local surpluses or deficits. This illustrates how coastal energy hubs, such as HIC Rotterdam, can integrate intermittent offshore wind into the broader energy system through a mix of direct use, storage, and conversion technologies.

Electricity Market Design

The design of the electricity market determines how electricity is traded, priced, and delivered across the energy system. As outlined by Laurens de Vries [26], the current Dutch electricity market structure consists of a wholesale and retail layer, supported by institutional frameworks and physical grid infrastructure (see Figure 2-2). The Netherlands operates an energy-only market, meaning that generators are only compensated for the electricity they produce and sell, with no separate payment for maintaining available capacity. Within the wholesale market, electricity is traded through mechanisms such as the power exchange and bilateral contracts. Balancing markets and import/export capacity allocation mechanisms help ensure reliability, while system operators and network managers oversee physical delivery across the transmission and distribution networks.

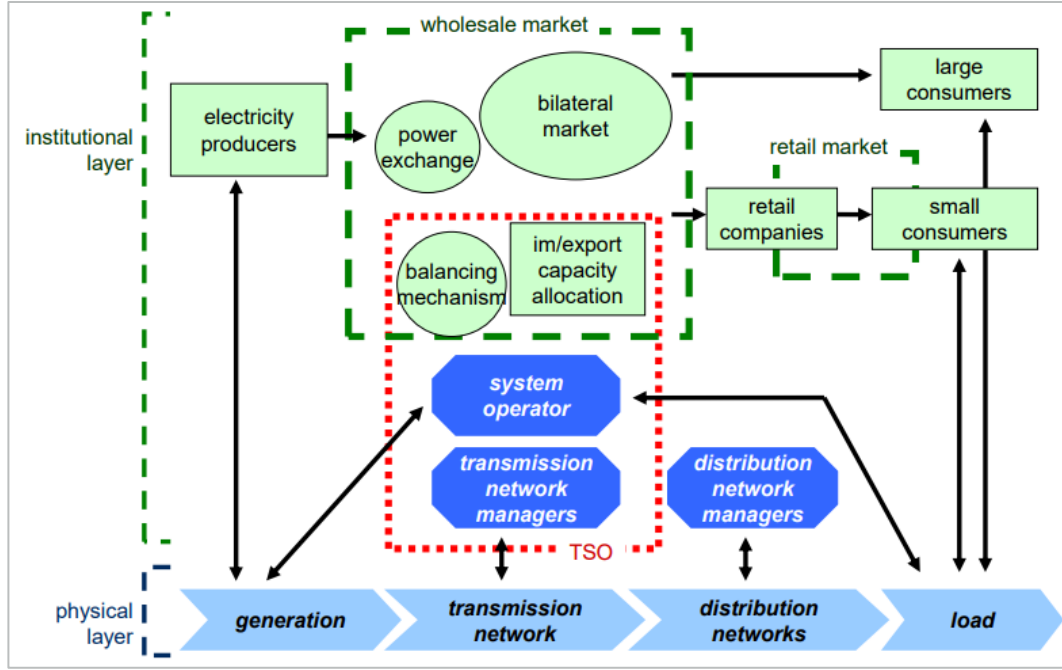


Figure 2-2: Diagram of the Dutch Electricity System [26]

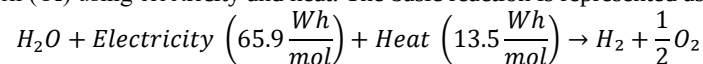
This thesis focuses specifically on the bilateral market, where electricity is traded directly between producers and consumers, often through long-term agreements known as Power Purchase Agreements (PPAs). PPAs are increasingly important for electrolysis-based hydrogen production. In a PPA, a consumer—such as an electrolyser operator—agrees to purchase electricity from a specific producer—such as an offshore wind developer—at a predetermined price and for a fixed duration. These agreements bypass the power exchange and offer price certainty for both parties, hedging them against volatile spot market prices [27], [28]. For the producer, PPAs provide a stable revenue stream and support investment in renewable energy projects. For the consumer, particularly in the context of hydrogen production, they reduce electricity cost uncertainty—one of the main operational expenses of electrolysers [27]. Additionally, PPAs support vertical coordination and enable the development of integrated, local energy systems, such as the proposed green hydrogen value chain at HIC Rotterdam.

However, because renewable generation is variable and weather-dependent, electricity supplied through PPAs may not always align with the real-time electricity demand of electrolysers. Operators often need to procure additional electricity from short-term markets to maintain continuous hydrogen production. The Day-ahead market is the main short-term market where electricity is traded one day before delivery. Participants submit bids for each hour of the next day based on expected production or consumption, and prices are set hourly by matching supply and demand. If needed, the Intraday market allows last-minute adjustments just hours—or even minutes—before delivery. Additional flexibility is provided by congestion markets and balancing, which operate on shorter timescales ranging from hours to seconds [26], [29], [30]. These mechanisms are essential for maintaining grid stability and ensuring uninterrupted electrolyser operation.

Green Hydrogen Production

Hydrogen is commonly categorised by colour labels—such as grey, blue, and green—to reflect its production method and associated greenhouse gas emissions [31]. In the European Union, only hydrogen that meets the Renewable Fuels of Non-Biologic Origin (RFNBO) criteria under the RED II and RED III directives is considered ‘green’. These criteria require additionality, temporal correlation, and geographical proximity between the renewable electricity source and the electrolyser, as explained further in Section 2.2.3 [32].

Green hydrogen is produced through water electrolysis, a reaction in which water (H_2O) molecules are split into hydrogen (H_2) and oxygen (O_2) using electricity and heat. The basic reaction is represented as follows [33]:



When powered exclusively by renewable energy sources such as wind, solar, or hydropower, this process produces no direct greenhouse gas emissions, qualifying the resulting hydrogen as ‘green’. By contrast, grey hydrogen is produced from natural gas, while blue hydrogen also relies on natural gas but incorporates carbon capture and storage (CCS) to reduce CO₂ emissions [34].

Green hydrogen can have several applications in areas such as HIC Rotterdam. It can replace grey hydrogen in high-emission industrial sectors, reduce natural gas consumption by injecting hydrogen into gas networks, and balance seasonal electricity supply and demand through hydrogen storage. Its value chain involves multiple stages—including production, compression, storage and transportation—allowing integration across multiple sectors and energy systems [34].

Currently, the three most developed electrolysis technologies are: Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM) electrolysis, and Solid Oxide Electrolysis Cells (SOEC), each with distinct advantages and limitations [35]. AWE is the most mature and cost-effective option for steady operation but is less responsive to fluctuating electricity inputs. PEM electrolysis responds quickly to variable renewable electricity but is more expensive due to the use of rare materials. SOEC operate at high temperatures and offer high efficiency, especially when coupled with industrial heat sources, though they remain at an early stage of commercialisation.

Green Hydrogen Import

There are several ways to import hydrogen, each with its own efficiency, technological readiness, and scalability. According to a study [36], the most efficient and mature method is hydrogen transportation via pipelines. Other options include shipping hydrogen derivatives such as ammonia, methanol, and synthetic natural gas too import terminals. However, derivatives often require reconversion to hydrogen, leading to inefficiencies and energy losses.

For HIC Rotterdam, importing hydrogen derivatives, like ammonia and methanol, is the most feasible option due to the availability of existing port and shipping infrastructure [18], [23]. Additionally, further pipeline transport of imported/produced green hydrogen could be facilitated through the “Waterstofnetwerk Nederland”, a planned hydrogen network connecting (inter)national industries [11].

An overview of the most common hydrogen transport routes, including the pipeline route, clean ammonia route, liquefied hydrogen route, and the liquid organic hydrogen carrier (LOHC) route, is shown in Figure 2-3. Each route involves specific conversion, storage, and reconversion steps, which influence the overall cost, efficiency, and environmental impact of the hydrogen supply chain [18].

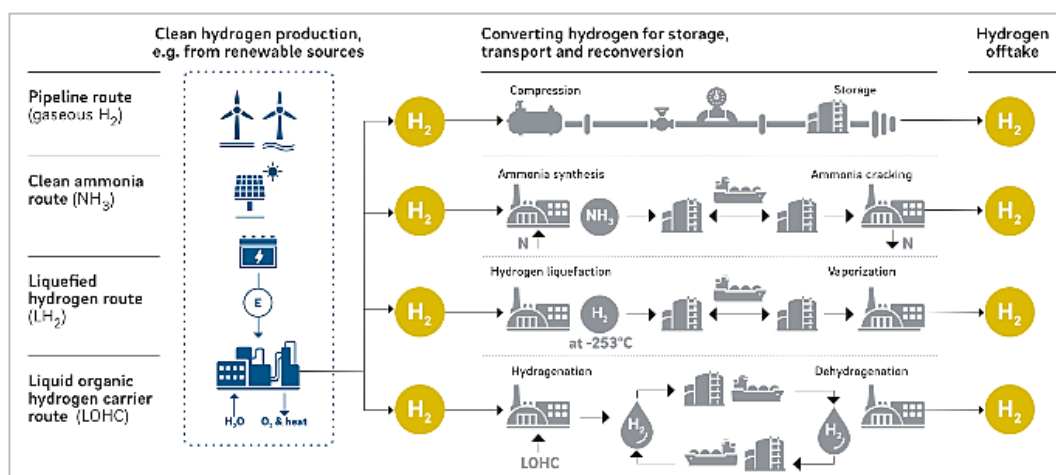


Figure 2-3: Leading Carriers for Large-Scale Hydrogen Transportation [18]

Energy Storage

Electricity

Electricity storage—particularly through large-scale batteries—plays an increasingly important role in balancing supply and demand within the future electricity system dominated by variable renewable sources such as solar and wind. As generation and consumption must be in continuous balance, storage contributes to system flexibility by absorbing

temporarily surpluses and compensating for shortfalls. Batteries can deliver this flexibility by participating in wholesale and balancing markets (as discussed in Section Electricity Market Design). Additionally, they help to prevent or resolve grid congestion at local level, especially during periods of peak demand or limited grid capacity [29].

In HIC Rotterdam, an area where electricity demand is growing and large-scale renewable generation (such as offshore wind from the VAWOZ programme) is being integrated, electricity storage can play an important role. Strategically placed batteries increase system flexibility, help to cope with peaks in supply and demand, and reduce grid constraints—all without the need for expanding infrastructure. This function is particularly important given the region’s structural congestion (see Section Grid Constraints and Infrastructure Developments) and the drive towards industrial electrification [11].

Hydrogen

As green hydrogen production increases, dependence on weather and seasonal patterns also grows, creating a need for large-scale storage to buffer fluctuations in supply [37]. Even in low-production scenarios, a significant volume of weather- and seasonally dependent hydrogen storage seems essential. This was illustrated in a simulation by Strategy& [37], which used 1987 as an extreme—‘Dunkelflaute’—weather year. Compared to a more typical year like 2015, the required storage capacity nearly doubled. This underlines the importance of underground storage in ensuring system reliability. Several hydrogen storage technologies exist, including underground pipelines, above-ground cylinders, salt caverns, and depleted gas fields [37], [38]. Among these, salt caverns and depleted gas fields are considered the most suitable for storing hydrogen at large scale.

In the context of HIC Rotterdam, the need for underground hydrogen storage depends on the degree of integration with international hydrogen markets [38]. Key factors include the balance between domestic production and imports, and whether the Netherlands becomes a hub for global hydrogen trade. Frequent imports—via ship or pipeline—from regions with abundant solar and wind energy could reduce the need for long-term storage. However, in pipeline-based transport scenarios, underground storage will likely remain essential as a system buffer for gaseous hydrogen.

The Hydrogen Landscape

The transition to a hydrogen-based energy system is not only a technological innovation, but also a complex socio-technical transformation shaped by interdependent economic, institutional, and political factors. The Multi-Level Perspective (MLP) framework developed by Geels [39] provides a useful lens to understand how such transitions unfold, including the hydrogen landscape in the Port of Rotterdam. The MLP distinguished between three interacting levels:

- Landscape developments (e.g., urgency of climate change, geopolitical concerns about energy security, technological breakthroughs)
- The existing socio-technical regime (fossil-based systems)
- Emerging technological niches (e.g. green hydrogen)

Landscape pressures are disturbing the stability of the current fossil-fuel-based system and creating new ‘windows of opportunity’. At the same time, niche innovations, such as hydrogen production from offshore wind, hydrogen import terminals, and pilot-scale electrolysis projects, are undergoing learning and scaling processes. As these niches mature and the regime weakens, systemic reconfiguration becomes increasingly feasible. In the context of the Port of Rotterdam, this multi-level dynamic is clearly visible through significant investments in offshore wind integration, hydrogen production and hydrogen import terminals [23], [40], [41], [42], [43].

2.2.2 Technical and Economic Fundamentals of Hydrogen Supply

Grid Constraints and Infrastructure Developments

The scalability of green hydrogen production in the Netherlands, particularly in the port of Rotterdam, depends heavily on the timely development and reinforcement of supporting infrastructure. This includes sufficient offshore wind landing capacity, electrolysis facilities, energy storage systems, and a hydrogen transport network. According to the CES Rotterdam-Moerdijk [11], 7.4 GW of offshore wind capacity is expected to come ashore in Rotterdam by 2030. Significant upgrades are required to accommodate this: new offshore substations, extended high-voltage grid

connections and expanded transmission lines, especially towards the Maasvlakte area. However, the North Sea Energy Outlook [6] warns that without these upgrades, the integration of offshore wind will face severe constraints due to limited landing sites, insufficient transformers, and cable bottlenecks, leading to delays and potential cost overruns.

Figure 2-4 highlights current electricity congestion zones in the Rotterdam industrial cluster [44], [45], underlining the acute shortage of transport capacity. [46] predicts that even under accelerated II3050 grid expansion scenarios, severe congestion risks will remain. Physical space limitations for new substations and permitting delays are key barriers. Total investments for energy infrastructure upgrades are expected to range between €30–50 billion by 2050. These challenges underscore the need for decentralised and flexible hydrogen production systems, ideally located near electricity generation sites.

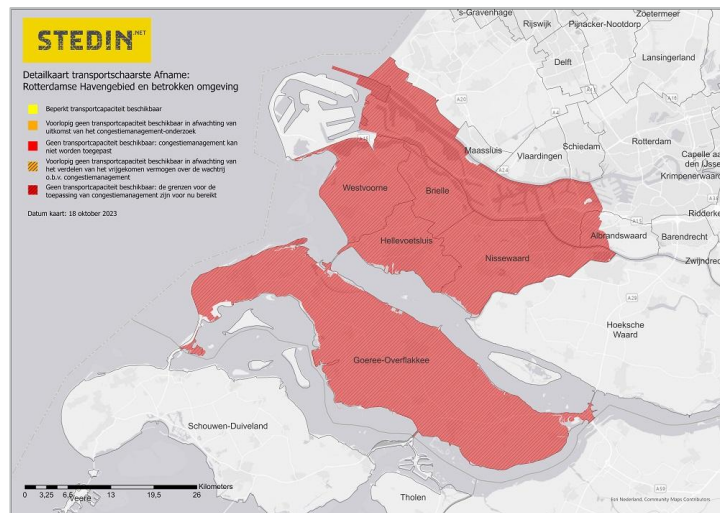


Figure 2-4: Electricity transport congestion in HIC Rotterdam [44], [45]

To address these constraints, the Port of Rotterdam is actively developing an integrated energy hub. As shown in Figure 2-5, this includes key infrastructure such as landing points, electrolyser hubs, hydrogen import terminals, and the planned Delta Rhine Corridor, a critical pipeline linking Rotterdam to inland industrial clusters [11].



Figure 2-5: Planned infrastructure for offshore wind and hydrogen at Port of Rotterdam [11]

In parallel, the development of the national hydrogen backbone, plays a crucial role in distributing hydrogen across regional and industrial clusters. Its phased rollout began in 2023 and is structured in four phases [47]:

- Phase 1 (2023–2026): Initial deployment in Rotterdam, operational by 2026
- Phase 2 (before 2030): Expansion to coastal clusters and connection to storage in Salt Caverns in Zuidwending
- Phase 3 (2031–2033): Interconnection of industrial clusters and integration with the Delta Rhine Corridor
- Phase 4 (post-2033): Further reinforcement of the network.

Cost Drivers

The Levelised Cost of Hydrogen (LCOH) is determined by several factors for domestic production and imports. For electrolysis, the main factors are electricity prices, the efficiency of electrolysis plants, and infrastructure scale effects, in particular, reductions in electrolysis plant CAPEX per MWe [19], [28]. Electricity purchases typically account for 40-50% of domestic LCOH. Standard grid tariffs can add about €2/kg H₂ to production costs [27], [48], while the efficiency of electrolyzers (65-70%) determines electricity consumption per kilogram [27]. For imports, additional cost drivers include the conversion of hydrogen into ammonia, maritime transport, storage, and reconversion back to hydrogen.

Electrolysis

As shown in Figure 2-6, the LCOH for proposed electrolyser projects in the Netherlands in 2024 is estimated at around €13.7/kg [27]. This breakdown shows that electricity costs (€5.19/kg) and TenneT grid tariffs (€2.07/kg) together account for more than half of the total production costs. Next to another large contribution of Unit Capital Expenditure (UCC), operation and maintenance (O&M), and stack replacement costs contribute to a smaller share. This emphasises that for electrolyzers in the Netherlands, reducing electricity prices and grid connection charges is at least as important as lowering CAPEX in order to reduce the LCOH.

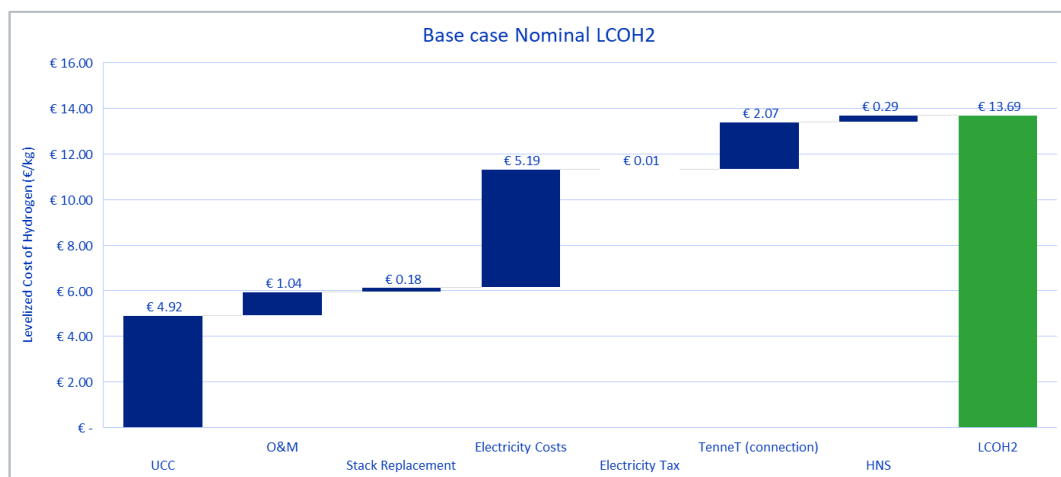


Figure 2-6: Current Levelized Cost of Hydrogen (LCOH) for Dutch electrolyser projects, showing cost breakdown [27]

According to [27], [48], and the 10-year forecast of TenneT [49], the grid tariffs are expected to increase even more by ~4.5% per year. In fact, the relevant grid tariff for large-scale electrolyzers has already more than quadrupled between 2021 and 2024, increasing from €32.80/kWe/year to €143.57/kWe/year. As can be seen on the right-hand side of Figure 2-7 below, TenneT's projections suggest a further increase of ~33% by 2031 and ~58% by 2034 compared to 2024 levels. As can be seen on the left-hand side, these rising costs are driven mainly by grid expansions to accommodate the growing offshore wind portfolio, such as the VAWOZ program (see Section Offshore Wind Policy - VAWOZ).

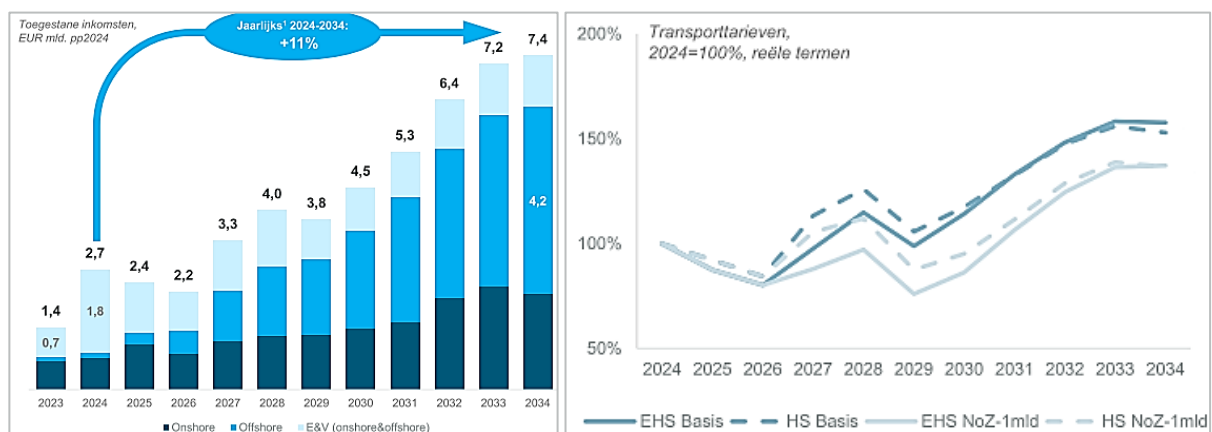


Figure 2-7: TenneT's 10-year forecasts for grid costs (left) & tariffs (right) [50]

Hydrogen Import

As outlined by TNO [51] and shown in Figure 2-8, the largest additional costs in hydrogen import supply chains, such as ammonia, come from the conversion and reconversion steps, together adding approximately €1.5–2.0/kg. Shipping costs between Morocco, Australia, and Europe remain relatively modest (~€0.2–0.4/kg), while export and import terminal operations add around €0.2–0.5/kg. Despite these drawbacks, imported hydrogen from regions with structurally lower electricity prices retains a significant cost advantage over domestic Dutch production.

Figures 2-8 below illustrates that while carrier conversion inefficiencies are significant in the supply chains of imported hydrogen, the advantage of much lower renewable electricity prices abroad largely offsets these additional costs, which creates the cost-competitiveness of imported hydrogen over domestic production.

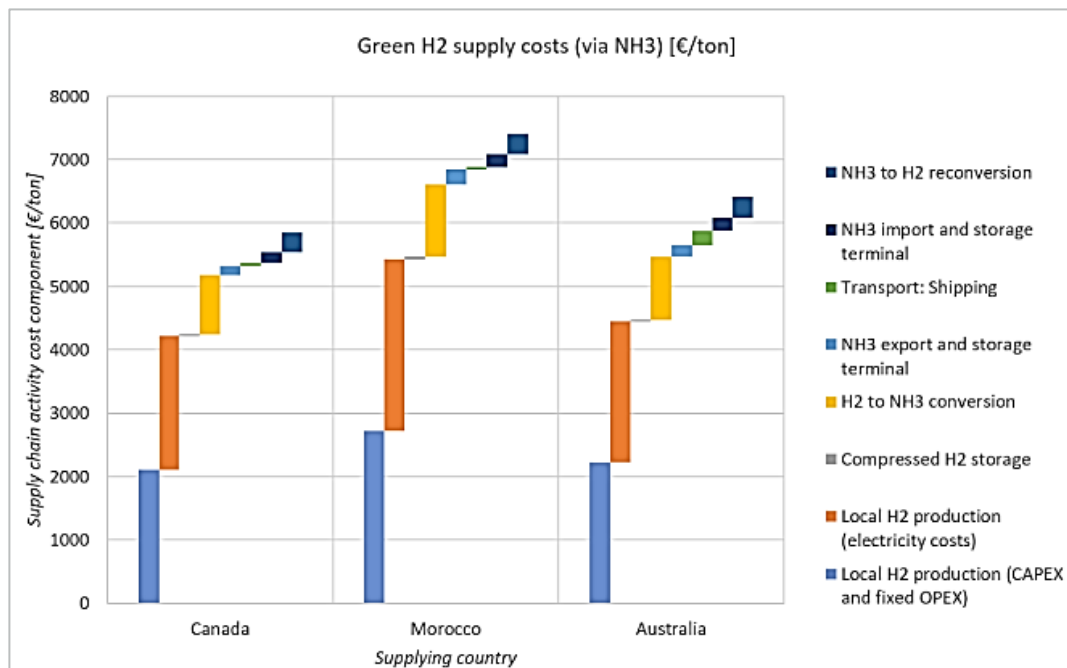


Figure 2-8: Green hydrogen supply (via ammonia) chain cost-component breakdown [51]

Cost-Competitiveness of Import vs. Domestic Regions

The competitiveness of the hydrogen supply chains is mainly determined by production costs, transport costs, and scalability. In the Netherlands, green hydrogen production is expected to cost €5.6–8.0/kg in 2040, depending on electricity prices and electrolyser efficiency, while imports from regions such as Morocco, Australia, Canada, Oman, Iceland, the UK and Saudi Arabia are expected to cost between €3.5 and €5.6/kg [19]. Therefore, it is expected that Europe will become a net importer of green hydrogen in the long term. According to IRENA [52] Countries such as the Netherlands, Belgium, Germany, France, and Italy are likely to rely on imports, whereas Spain, Portugal, Norway, and the UK may become net exporters.

Figure 2-9 presents the global technical annual potential in 2050 to produce green hydrogen for less than €1.50/kg, expressed in Giga tonnes (Gton) of hydrogen [19]. The figure shows significant regional differences, with sub-Saharan Africa (~22.5 Gton), North Africa, Middle East (~16.8 Gton), North America (~10.9 Gton), Oceania (~10.6 Gton), and South America (~9.2 Gton) offering the greatest potential at low cost compared to Europe (~0.7 Gton). These numbers reflect the availability of optimal renewable resources, such as solar and wind, and sufficient land area for large-scale hydrogen production facilities, as also shown in Figure 1-1.

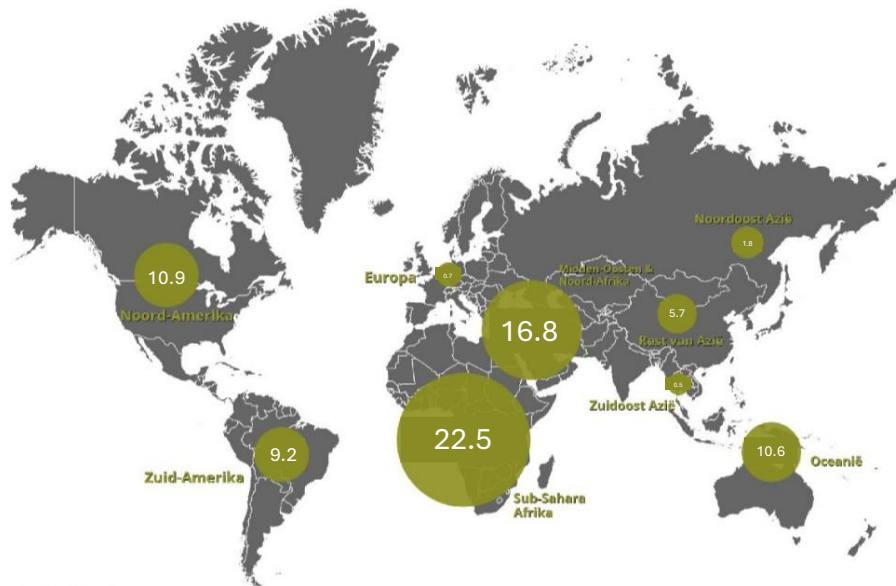


Figure 2-9: Technical potential in 2050 (in Gton) for green hydrogen production at <€1.50/kg (adapted from [19])

2.2.3 Geopolitics and Policy

Geopolitical Dimensions

The European Union, and thereby the Netherlands and Port of Rotterdam, faces major geopolitical challenges in securing a stable hydrogen future. As shown in the previous section and highlighted by Quitzow et al. [53], Europe's limited domestic renewable potential, and associated dependence on imports, emphasize the need for a diversified hydrogen supply mix to safeguard against geopolitical instability.

The war in Ukraine has further reinforced the urgency of reducing dependence on Russian energy, as point also highlighted by the International Energy Agency (IEA) in its 2024 report [3]. At the same time, Donald Trump's re-election raises concerns about possible shifts in US energy policy, especially with regard to clean energy initiatives and international cooperation. This is already demonstrated by his decision to withdraw the US from the Paris Climate Agreement [54].

In this context, the EU must balance internal fragmentation and competition from global players such as China and the US to maintain its leadership in hydrogen technology and ensure energy security [53]. Crucial to these efforts is the establishment of strategic partnerships, particularly with countries that can supply low-cost renewable hydrogen.

European Union Hydrogen Policy

To accelerate the hydrogen transition, the EU introduced the REPowerEU plan [5], which sets a target of producing and importing combined 10 million tonnes (Mton) of renewable hydrogen by 2030. A key part of this policy is the certification for Renewable Fuels of Non-Biological Origin (RFNBO) [55]. To qualify as RFNBO, hydrogen must meet three key requirements [32]:

- **Additionality:** Hydrogen must be produced using new renewable electricity, or from a grid with at least 90% renewable share, ensuring it does not divert existing renewables [56].
- **Emission reduction:** Hydrogen production must deliver at least a 70% reduction in greenhouse gas emissions compared to grey hydrogen.
- **Sustainability tracking:** The entire supply chain must be traceable through a mass balance system.

These criteria apply not only to green hydrogen but also to its derivatives such as ammonia, methanol, LOHCs (liquid organic hydrogen carriers), and other synthetic (transport) fuels.

In parallel, the Renewable Energy Directive III (RED III) sets specific targets for RFNBOs: by 2030, they must account for at least 1% of the transport sector's energy demand and 42% of industrial hydrogen demand, rising to 60% by 2035 [32]. These measures are intended to provide regulatory clarity, ensure environmental standards and stimulate market demand for clean hydrogen across multiple sectors.

Dutch Policy

Offshore Wind Policy - VAWOZ

To support the large-scale expansion of offshore wind capacity and ensure its effective integration into the national energy system, the Dutch government initiated the Verkenning Aanlanding Wind op Zee (VAWOZ) programme [10]. VAWOZ focuses on the spatial planning and coordination of grid connections and landfall locations for offshore wind projects in the period beyond 2030. The programme evaluates technical, spatial, environmental, and societal factors to determine optimal sites for electricity landing and system integration. Figure X-2 in Appendix B presents a national overview of all potential offshore wind landing sites considered under VAWOZ (2031-2040). It highlights the geographic spread of future offshore wind zones and their prospective connections to the Dutch coastline. This framework ensures alignment between offshore wind development, port infrastructure, and the evolving energy grid.

Within this context, the Haven Industrieel Complex (HIC) Rotterdam is identified as a critical hub due to its strategic location, existing industrial base, and potential for large-scale hydrogen production. The HIC offers a unique combination of energy demand, access to deep-sea offshore wind zones, and proximity to high-voltage grid infrastructure and future electrolyser sites. These characteristics make it an ideal location for integrated offshore wind and green hydrogen value chains.

Figure 2-10 below provides a zoomed-in view of offshore wind zones and cable routes expected to connect to the Port of Rotterdam between 2031 and 2050 [56]. It underscores the high concentration of offshore wind electricity (~1/3 of Dutch Capacity) expected to land at Maasvlakte, where approximately 7.4 GW is planned by 2031. This reinforces the central role of HIC Rotterdam in the Dutch offshore wind integration and its transformation into a flexible, hydrogen-enabled energy hub.



Figure 2-10: Potential VAWOZ Landfalls in the Port of Rotterdam (2031-2050) (adapted from [56])

Hydrogen Policy

National hydrogen policy in the Netherlands is established in the Klimaatakkoord [2], with further specification provided by the Routekaart Waterstof [57] and the Nationaal Plan Energiesysteem (NPE) [4]. The government targets the deployment of 6–8 GW of electrolysis capacity by 2030 and plans for substantial hydrogen imports via terminals in HIC Rotterdam. According to the Programma Energiehoofdstructuur (PEH) [58], preferred areas for large-scale electrolysis are located near offshore wind landing points and the hydrogen network, making HIC Rotterdam a key landing site. This policy aims to minimize the need for additional transport capacity for electricity and reduce grid congestion, ensuring efficient integration of wind energy into the electrolyser network.

Financial support mechanisms include the ATR85 regulation, a proposed electricity transport tariff that allows TenneT to limit grid access for large electrolysers up to 15% of the time, in exchange for exemption the kW-based contract tariff. According to [27], this arrangement can result in ~50% saving of grid tariffs. This mechanism is particularly relevant for flexible electrolysis operations aligned with renewable energy availability.

Another important policy development is the introduction of the refinery route (also ‘raffinageroute’). This involves the use of renewable hydrogen in refinery production processes, replacing the grey hydrogen traditionally used from natural gas. The government has decided to apply a correction factor (adjustment factor) of 1.0 for the use of renewable hydrogen in refineries [59], [60]. This means that the use of renewable hydrogen in refineries will count towards European obligations just as much as its direct use in transport. This decision aims to stimulate the use of renewable hydrogen in refineries by providing a more favourable economic framework, encouraging investment in electrolysis projects.

Despite these incentives, NLHydrogen (the Dutch Hydrogen Industry Association) recently reported that the Nieuw Klimaatpakket and the Voorjaarsnota 2025 reforms still do not provide the systemic financial support needed to achieve the 4 GW electrolyser deployment milestone by 2030 [61]. In particular, uncertainties around tariff exemptions and the long permitting lead times for new hydrogen infrastructure are mentioned as remain key bottlenecks.

Port of Rotterdam Strategy

The Port of Rotterdam bases its energy transition on four pillars [62]. These pillars align with the European & Dutch Climate goals of reducing CO₂ emissions by 55% by 2030 and achieving CO₂ neutrality in 2050 (see Figure 2-11 below).



Figure 2-11: The Port of Rotterdam's 4 Pillars of the Energy Transition [62]

A central ambition is to position the port as Europe's leading hydrogen hub, combining large-scale domestic production with significant imports [63]. The Cluster Energy Strategy (CES) outlines four possible development pathways [11]:

- “Connected Deep Green”, with an emphasis on full integration of renewable energy;
- “Wake-Up Call”, assuming a slow development of the hydrogen market;
- “Regional Well-being”, promoting regional self-sufficiency;
- “Protective Markets”, assuming geopolitical fragmentation.

To realise its hydrogen ambitions in the near future, the Port Authority plans to develop 2.5 GWe of electrolysis capacity by 2030 and process up to 4 Mton of hydrogen imports per year [63]. Supporting infrastructure projects include the development of eight new import terminals and the construction of an ammonia cracker capable of processing 1 Mton of hydrogen per year [23].

2.3 Conclusions on Literature

2.3.1 Scientific Literature

Table X-3 in Appendix A provides a detailed overview of the number of citations, geographical focus, and scale of occurrence of the selected scientific literature on hydrogen-related topics. The literature reflects growing academic interest in offshore wind-based hydrogen production, energy system integration in industrial port areas, and techno-economic optimisation. Several studies, such as [64], for Brazil and [65] for Ireland explore levelized costs of hydrogen from offshore wind, while [66] examine the viability of energy carriers such as ammonia and LOHCs for long-distance hydrogen transport. Furthermore, [67], [68] offer comparative analyses of local production versus hydrogen imports, although these focus on Germany, Portugal, and Australia.

Although several studies [69], [70], [71], [72] consider hydrogen in the context of the decarbonisation of industrial ports, and [73] highlights the integration of energy systems in Norwegian ports, none of the selected studies focus specifically on the Netherlands or the Port of Rotterdam. This represents a significant gap in the literature, given the port's status as one of Europe's most important seaports and its role in the energy transition as an industrial cluster and potential hydrogen hub.

In summary, the scientific literature shows two main limitations: A lack of case-specific studies focusing on Dutch hydrogen supply, especially in the context of the Port of Rotterdam; A limited number of comparative evaluations analysing both offshore wind-based hydrogen production and hydrogen imports under techno-economic and system constraints. Filling this gap could provide valuable insights for designing integrated hydrogen supply strategies and promoting port decarbonisation in the Dutch and broader European context.

2.3.2 Grey Literature

As shown in Table X-4 in Appendix A, developing large-scale electrolysis capacity in the Port of Rotterdam is well aligned with both national and European hydrogen goals. According to the Nationaal Programma Verduurzaming Industrie (NPVI) [72], the Dutch Climate Accord aims for 3-4 GWe electrolysis capacity by 2030 and 8 GWe by 2032, while the EU Fit for 55 aims for 40 GWe by 2030.

Long-term system integration is addressed in the Nationaal Plan Energiesysteem (NPE) [4], which outlines a vision for connecting renewable electricity and hydrogen within the Dutch energy system. Complementing this, the Programma Energiehoofdstructuur (PEH) [58] emphasises the need to expand national energy infrastructure —both electricity and hydrogen —crucial for scaling up hydrogen production and distribution.

At the port level, the Port of Rotterdam aims to realise 2.5 GWe of electrolysis capacity by 2030 and to land approximately one-third of the planned 50 GWe offshore wind capacity (to be built between 2030–2050), either as electricity or hydrogen produced at sea [63]. This ambition is supported by the Verkenning Aanlanding Wind op Zee (VAWOZ) programme [10], which promotes the integration of offshore wind electricity into the energy system to enable green hydrogen production.

Additionally, the port is preparing to become a major hydrogen import hub, with plans to establish eight import terminals for ammonia, LOHCs, or liquid hydrogen [63]. By 2030, this infrastructure will enable a yearly throughput of 4 Mton of hydrogen imports, on top of 0.6 Mton of domestic production (0.25 Mton green and 0.35 Mton blue hydrogen). Combined, this would represent about 20% of the European Commission's REPowerEU target of 20 Mton hydrogen by 2030 [5].

In conclusion, the grey literature highlights the central role of the Port of Rotterdam in advancing national and EU hydrogen targets. Through its planned production capacity, (planned) offshore wind connections, and import infrastructure, the port is positioned to make a significant contribution to the development of a green hydrogen economy in Europe.

2.4 Knowledge Gap and Research Questions

The literature review shows a growing academic and policy interest in (green) hydrogen production, hydrogen imports, and the integration of offshore wind electricity. However, several gaps persist—particularly in the context of the HIC Rotterdam.

First, existing studies lack a location-specific, techno-economic comparison of domestic hydrogen production versus imports tailored to the unique context of HIC Rotterdam. While existing research such as [19], [27], [51], [67] explores (the costs of) hydrogen supply chains and the feasibility of electrolysis in general, few studies account for key local factors such as offshore wind variability, infrastructure constraints, and the industrial energy demand specific to HIC Rotterdam. This is a significant omission given the port’s strategic role as a hydrogen hub, offshore wind landing point, and industrial cluster in both the Dutch and European energy systems.

Second, while governmental reports such as [4], [11], [58] outline ambitious hydrogen strategies for HIC Rotterdam—including domestic production and import scenarios—these sources typically lack a consistent analytical framework to assess cost-competitiveness and system relevance. They fall short in accounting for uncertainties such as volatile electricity prices, rising grid tariffs [48], evolving capital costs, and shifting electricity and hydrogen demand patterns.

Third, studies such as [17], [18], [19], [51] consistently suggest that regions like Sub-Saharan Africa, North Africa, the Middle East, and Oceania are likely to offer structurally lower long-term hydrogen production costs compared to Europe. Yet there is limited integration of this insight into comparative energy system models relevant to HIC Rotterdam.

From this review, three core knowledge gaps emerge:

- **Lack of location-specific techno-economic analysis:** Existing studies do not fully incorporate HIC Rotterdam’s unique offshore wind profiles, infrastructure bottlenecks, and industrial consumption patterns.
- **Limited comparative system modelling:** There is a scarcity of studies that model domestic production and imports together, capturing their dynamic trade-offs under varying techno-economic conditions.
- **Unclear competitiveness thresholds:** It remains poorly understood under which circumstances domestic production can become cost-competitive with hydrogen imports.

Therefore, this study seeks to bridge these gaps by addressing the following main research question:

“Under which techno-economic and strategic conditions is onshore hydrogen production, powered by offshore wind, cost-competitive with ammonia-based hydrogen imports, while contributing to a robust hydrogen and electricity system in the Port of Rotterdam?”

The objective of this study is to assess the competitiveness of offshore wind-based hydrogen production relative to hydrogen imports in the Port of Rotterdam under varying techno-economic conditions. It further aims to explore the strategic implications of these conditions. By using scenario-based system modelling with Linny-R, this research will provide insights into the conditions required for a robust hydrogen and electricity system. The findings aim to support policymakers and industrial stakeholders in shaping the energy transition in major port regions such as HIC Rotterdam.

Sub-Questions

To effectively answer and guide the research addressing this main question, three sub-questions (SQs) have been formulated. Each sub-question targets a specific part of the analysis and contributes to the broader research goal through defined objectives:

SQ1: *“Which techno-economic factors most significantly affect the cost-competitiveness of onshore hydrogen production, powered by offshore wind, relative to ammonia-based hydrogen imports in the Port of Rotterdam?”*

- To identify and quantify the impact of key techno-economic drivers on the Levelized Cost of Hydrogen (LCOH), using sensitivity and cost comparison analyses.
- This enables prioritisation of drivers for system design and strategic intervention.

SQ2: *“Under which system combinations—of electricity and hydrogen supply, demand, and storage—does onshore hydrogen production, powered by offshore wind, provide a stable and cost-effective contribution to the electricity and hydrogen system in the Port of Rotterdam?”*

- To evaluate the operational feasibility and system-level value of domestic hydrogen production across varying supply-demand scenarios, using scenario-based experiments.
- The goal is to identify robust configurations that support flexibility, utilisation, and resilience.

SQ3: *“What are the strategic implications—of the electricity and hydrogen—system conditions under which onshore hydrogen production, powered by offshore wind, plays a stable and cost-competitive role for stakeholders in the Port of Rotterdam?”*

- To synthesise the techno-economic findings and assess their relevance for long-term strategy under uncertainty.
- This includes deriving recommendations for port authorities, industry actors, and policymakers.

Based on the sub-question results, the analysis compares domestic hydrogen production and imports in terms of cost and system integration. It evaluates the robustness and cost-effectiveness of different strategies under key uncertainties. This helps determine under what conditions offshore wind-powered electrolysis can be a competitive and reliable part of the HIC Rotterdam’s future energy system.

3 Methodology

This chapter outlines the research methodology applied in this study. It begins by presenting the overall research approach and the key methodological components, including the Modelling & Simulation Life-Cycle framework, Exploratory Modelling and Analysis, the use of Linny-R as the core modelling tool, and the XLRM framework. The section concludes with the 4 A's of energy security, which serve as the foundation for defining the Key Performance Indicators. Finally, the methodology is summarised in a research flow diagram that provides a structured overview of the different steps undertaken.

3.1 Research Approach and Methods

3.1.1 Modelling and Simulation Life-Cycle

To determine a robust balance between offshore wind -based hydrogen production and hydrogen imports at the port of Rotterdam, a modelling approach will be applied. This approach is well suited for analysing and visualising complex socio-technical systems which allows the optimisation of hydrogen supply strategies under different techno-economic and policy conditions. Following the approach described by Cetinkaya et al. [75], the Modelling & Simulation (M&S) lifecycle framework is used to ensure a systematic and transparent modelling process. This framework consists of five main stages: (1) problem definition, (2) conceptual modelling, (3) specification, (4) implementation and (5) experimentation. From the conceptual modelling phase, each phase is verified with its previous phase. Additionally, the experimentation phase is validated with the problem definition phase.

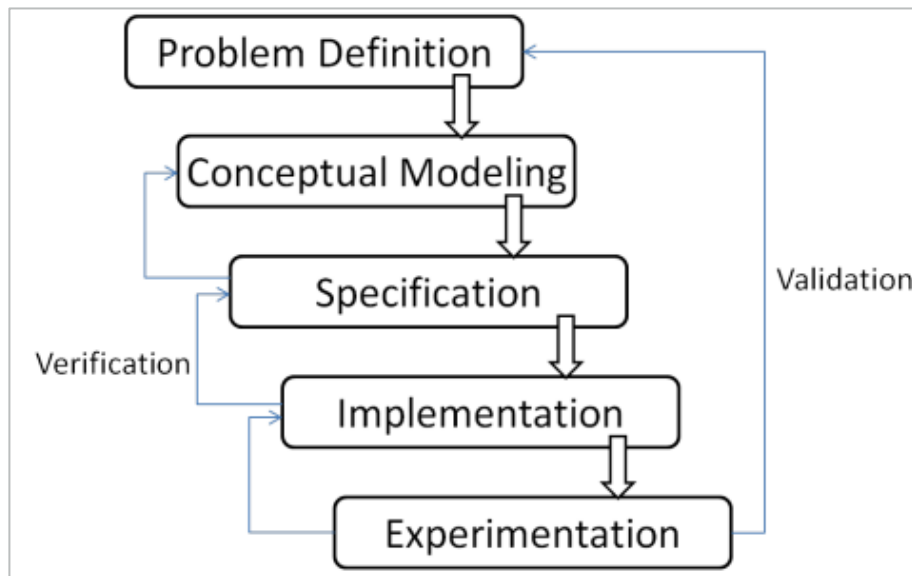


Figure 3-1: Modelling and Simulation Life-cycle [75]

3.1.2 Exploratory Modelling and Analysis

Exploratory Modelling and Analysis (EMA) is a computational approach used to analyse complex systems under deep uncertainty, situations where future developments (e.g., policy, technology, market dynamics) cannot be reliably predicted. Originally introduced by Bankes in 1993 [76], EMA does not aim to produce a single forecast, but instead explores a broad range of plausible scenarios to evaluate how different strategies perform across varying assumptions. In this thesis, EMA is used to explore the techno-economic trade-offs between domestic hydrogen production via offshore wind and hydrogen imports under different future conditions. This includes uncertainty in electricity prices, electrolyser CAPEX, hydrogen import costs, and policy interventions such as subsidies or grid tariff adjustments.

To implement EMA, the modelling tool Linny-R is used, developed by Pieter Bots [77]. Linny-R enables fast, scenario-based simulations of energy systems using Mixed Integer Linear Programming (MILP). Its graphical interface and built-in support for scenario management make it well suited for exploratory modelling. In this thesis, Linny-R is used to create a flexible hydrogen supply model for the Port of Rotterdam, define and run a large set of scenarios, and evaluate how different hydrogen supply strategies perform under uncertain futures. By combining EMA with Linny-R, this study identifies robust hydrogen infrastructure strategies that remain effective across a wide range of plausible conditions, rather than relying on a single optimal case.

Modelling Tool - Linny-R

As mentioned in the previous section, Linny-R is used as modelling tool for this research. Linny-R uses four fundamental modelling concepts to represent production systems: processes, products, levels, and rates. This structure makes it particularly suitable for analysing the complex energy system interactions within HIC Rotterdam. The ability of Linny-R to integrate various constraints and decision variables ensures that important aspects such as the intermittency of offshore wind, infrastructure constraints and hydrogen supply routes are represented.

One of Linny-R's main advantages lies in its graphical and transparent approach, which simplifies the formulation and interpretation of complex MILP problems. This improves the interpretability, traceability, and validation of model results [77]. The model's focus on process optimisation enables a clear review of the cost-effectiveness and feasibility of different hydrogen supply strategies. Furthermore, Linny-R supports flexible scenario-based modelling, enabling the exploration of a wide range of regulatory, economic, and technical conditions. Its ability to model interdependencies between processes and constraints makes it a powerful tool for formulating strategic recommendations for energy systems such as HIC Rotterdam.

Although Linny-R offers a structured and transparent method for investigating trade-offs at system level, the fact that it is based on linear optimisation and perfect foresight means that the results reflect an idealised system state. In practice, inefficiencies, deviating behaviour and uncertainties can lead to deviations from these results. Therefore, the findings should be interpreted as indications of possible trends and not as exact predictions. Moreover, as the model seeks simplification, it may omit certain technical or operational details. This may affect the accuracy of the results. To address this, the model is supplemented with external data from industry and policy sources, both for benchmarking the input and for validating the output afterwards. Lastly, large-scale modelling can be computationally intensive, requiring a balance between model detail and efficiency. By focusing on the most important decision variables while maintaining computational feasibility, the model will still provide meaningful insights into hydrogen supply strategies.

XLRM Framework

To support the scenario design and uncertainty analysis in this study, the XLRM framework is adopted. This framework, developed by Lempert et al. [78], is widely used in robust decision making and provides a structured way to explore complex systems under deep uncertainty. It enables researchers to examine how different strategies perform across a wide range of plausible futures by systematically organizing the key components of a model. The four components of the XLRM framework are:

- **Exogenous uncertainties (X):** Factors outside the control of decision-makers, but which can significantly influence outcomes.
- **Policy levers (L):** The strategic actions or interventions that decision-makers can choose to implement.
- **Relationships (R):** The internal structure of the system that describes how decisions and uncertainties interact over time.
- **Performance metrics (M):** The criteria used to evaluate the outcomes of different strategies.

Figure 3-2 provides a conceptual illustration of the XLRM framework. It highlights how external uncertainties and policy decisions influence system behaviour, which in turn produces outcomes that can be evaluated through performance metrics.

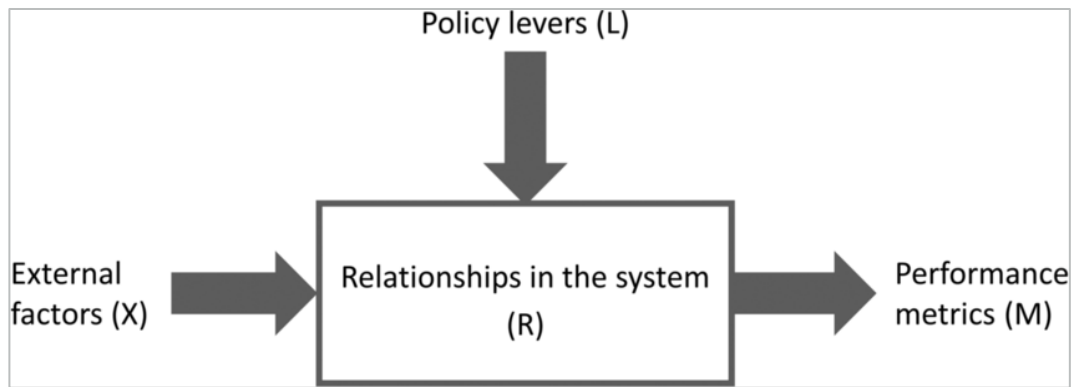


Figure 3-2: Conceptual overview of the XLRM framework [78]

The XLRM framework serves as a guiding structure for this thesis, linking the modelling process in Linny-R to the broader decision-making context. It supports the development of a wide range of future scenarios, ensuring a consistent and comprehensive approach to exploratory modelling and robust strategy evaluation.

Evaluation by 4 A's of Energy Security

To assess the performance of different hydrogen supply strategies under uncertainty, this study adopts the 4 A's of Energy Security framework developed by the Asia Pacific Energy Research Centre (APERC) [79]. This framework provides a comprehensive and multidimensional approach to evaluate the robustness and sustainability of energy systems, particularly in the context of energy transitions. The 4 A's are defined as follows:

- Availability: The physical presence of sufficient energy resources to meet demand, including the reliability of supply over time.
- Accessibility: The ease with which energy can be delivered to end-users, considering infrastructure constraints and geopolitical risks.
- Acceptability: The environmental and social compatibility of energy sources, including emissions, land use, and public support.
- Affordability: The economic feasibility of energy supply options, including both system-level costs and consumer pricing.

By applying this evaluative framework, the study ensures that the comparison between domestic hydrogen production and imports extends beyond cost alone. It captures broader strategic trade-offs, such as energy independence, infrastructure risks, and long-term sustainability, critical factors for the Port of Rotterdam's role in the Dutch and European future electricity and hydrogen system.

3.2 Research Flow Diagram

The figure below shows the Research Flow Diagram (RFD), providing a structured overview of the key steps of this study. The thesis research proposal functioned as initial input, followed by each phase through the Modelling & Simulation (M&S) life cycle. The first two sub-questions (SQs) are addressed during the experimentation phase, while the final phase focuses on answering the last SQ and synthesising findings to address the main research question. Each step builds on the previous one, includes iterative feedback loops and uses specific research methods, data sources and analytical tools to generate key insights.

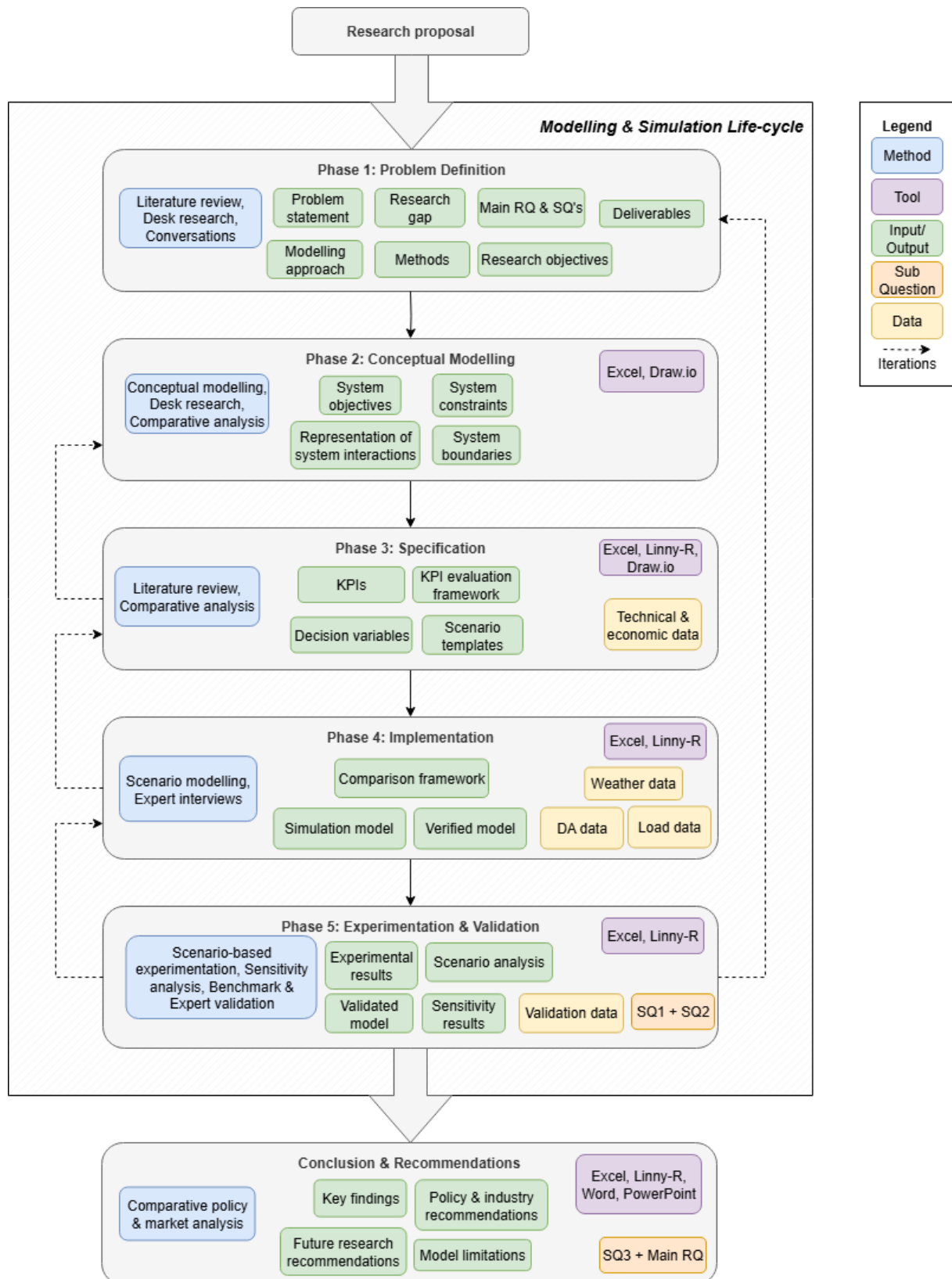


Figure 3-3: Research flow diagram using Modelling & Simulation (M&S) lifecycle framework [75]

4 Conceptualisation and Specification

As outlined in previous chapters, the (future) Dutch electricity and hydrogen system—particularly in the Port of Rotterdam—is increasingly interconnected through infrastructure developments, policy objectives, and industrial decarbonisation goals. This chapter supports the conceptualisation and specification phase of the modelling & simulation life-cycle, focusing specifically on hydrogen supply in the Port of Rotterdam area and beyond.

First, a high-level system overview is presented in form of a conceptual model. This is followed by a further explanation of the components within and outside the scope of this research. Lastly, the key performance metrics are discussed and structured into an XLRM-framework, aligning with the specification phase of the modelling-cycle.

4.1 Conceptualisation

Figure 4-1 presents a high-level system overview, highlighting the key components, flows, and interactions between electricity generation, electricity storage, hydrogen production, hydrogen imports, hydrogen storage, and electricity & hydrogen demand within the system. Crucially, the figure defines the scope of this research, which includes electricity supply from offshore wind and the high-voltage (HV) grid, electricity storage in large-scale batteries, hydrogen imports via ammonia shipments, hydrogen production through electrolysis, and hydrogen storage in salt caverns. The electricity-and-hydrogen demand is divided into HIC Rotterdam and the Hinterland. Elements outside the dotted boundary lie beyond the scope of this study.

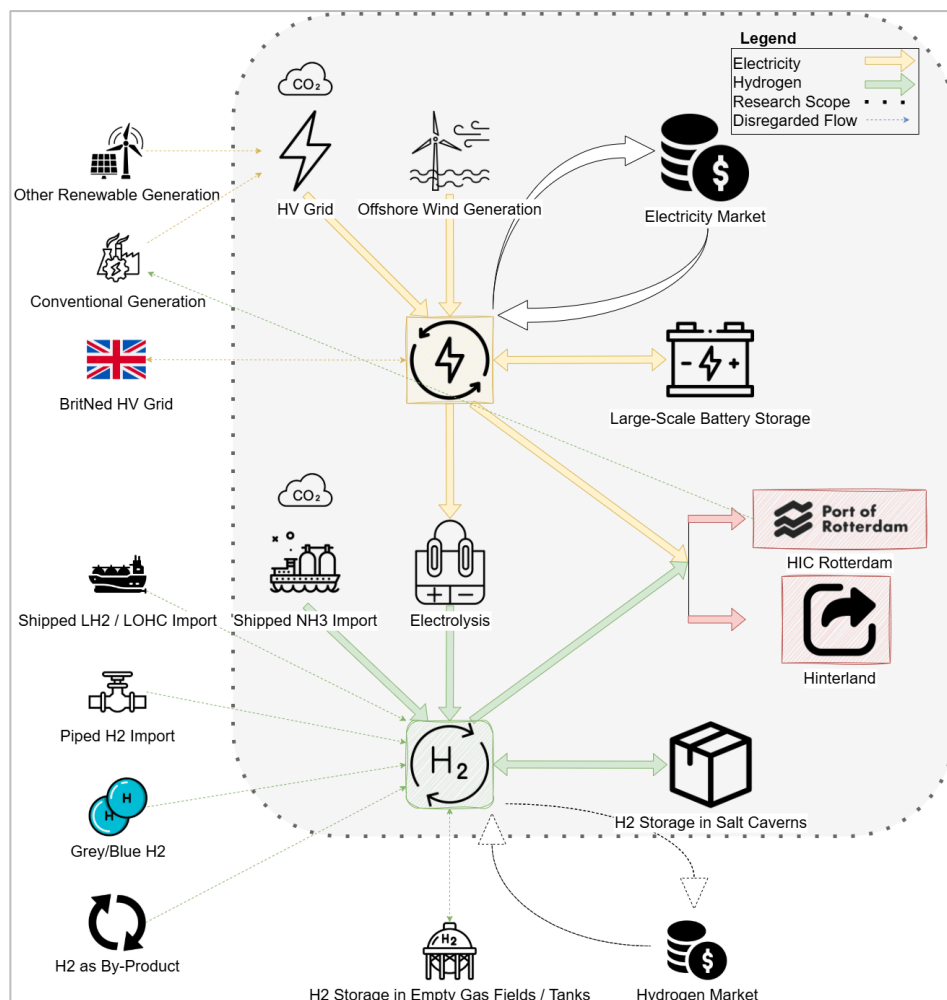


Figure 4-1: Conceptual Overview of the Electricity & Hydrogen System in the Port of Rotterdam & Hinterland

For clarity, Figure 4-2 presents the high-level system overview that includes only the components used in the Linny-R model.

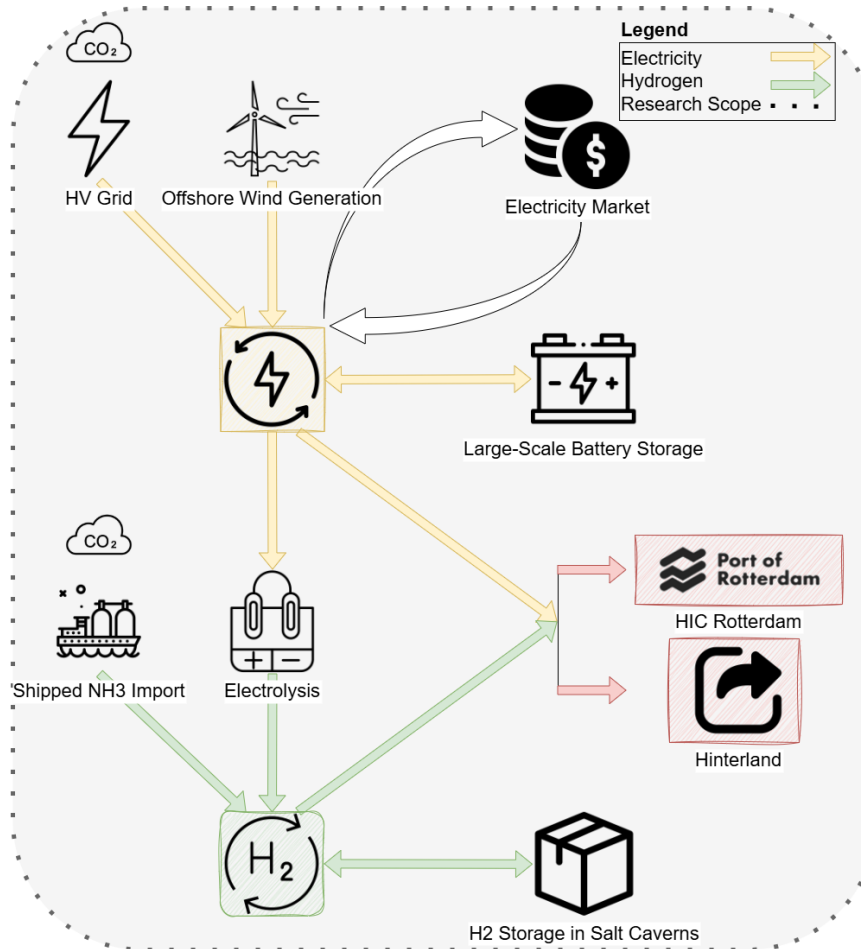


Figure 4-2: Conceptual Overview of the Model

The following sections provide a detailed discussion of the key components and relationships, both within and outside the defined scope of this research. Particular attention is given to how these elements interact within the energy system, such as offshore wind integration, grid electricity supply, hydrogen production and storage.

4.1.1 Electricity System

To simplify the complexity of the electricity system and assess the impact of the VAWOZ programme with its large-scale offshore wind integration in the Port of Rotterdam, the electricity system has been reduced to three main supply flows: supply by the HV grid (priced via historical day-ahead data), supply by offshore wind (partly under fixed power purchase agreements (PPAs), partly day-ahead (DA), and electricity to/from a large-scale battery (which buys and sells via day-ahead). These flows reflect key market mechanisms through DA prices and PPAs, and are used by three main consumers; electrolysis, HIC Rotterdam, and the hinterland. The following sections describe each component included and excluded from the model in more detail.

Electricity Generation

In addition to its strategic role in offshore wind integration (see Section Offshore Wind Electricity and Landfall), the Port of Rotterdam is a major hub for electricity generation due to its industrial demand and grid connectivity. The region currently hosts multiple power plants (Gas, Coal, and Biomass) with a combined installed capacity of ~3.9 GW [80]. To align with the sustainability objectives in the Port of Rotterdam, as outlined in Section Port of Rotterdam Strategy, a significant transformation of the electricity system is required. From 2030 onwards, coal-fired power plants will be phased out [25]. Furthermore, the Dutch government is planning new nuclear energy facilities, with the Maasvlakte identified as a potential site for two nuclear reactors with a combined capacity of around 3 GW [58].

The offshore wind electricity supply is based on capacity values derived from the VAWOZ programme projections (see Section Offshore Wind Policy - VAWOZ). These offshore parks are connected via inter-array cables to offshore HVDC platforms, which transport electricity through 2 GW DC cables to onshore converter stations. This setup is shown schematically in Figure 4-3, while Figure 4-4 provides a more technical cross-section of the offshore transmission system, including voltage levels and cable types used.

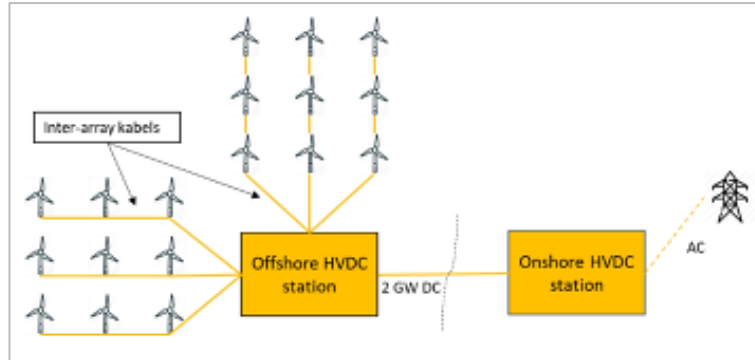


Figure 4-3: Schematic overview of a 2 GW offshore wind electricity connection [81]

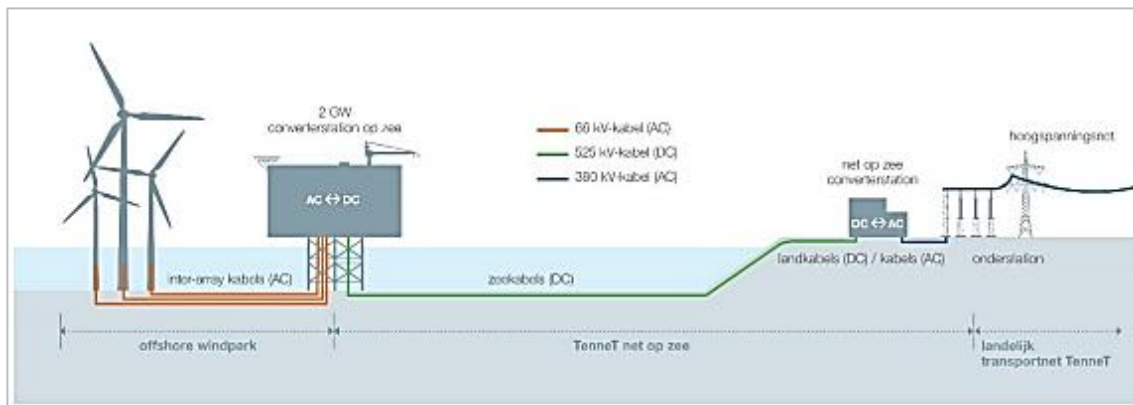


Figure 4-4: Technical cross-section of the offshore-to-onshore wind connection [82]

The BritNed interconnector, a 1 GW HVDC link between the Maasvlakte and the United Kingdom [81], is excluded from this study. As it is primarily used for international electricity trade and European market coupling, and not regional supply, it is assumed not to influence local electricity flows.

The grid electricity supply is a simplified aggregation of remaining sources such as onshore wind, solar, and conventional generation. Given their relatively low capacity (~500 MW) in the Port of Rotterdam [56], the weather dependent sources, onshore wind and solar PV, are excluded as separate flows and are instead included in the general HV grid supply. This distinction allows the model to differentiate between large-scale electricity from offshore wind and from the wider grid, with grid electricity assigned a dynamic emission factor based on future fuel mix projections [4], [83]. While electricity generation using hydrogen is technically feasible, it is not included in this study. As concluded by van Kaauwen [84] in 2024, green hydrogen is not yet widely applied in the industrial sector, and its use in hydrogen-fuelled gas turbine power generation remains uncertain and currently far too expensive to be considered a viable option at scale.

Electricity Storage

According to CE Delft [85], lithium-ion batteries are currently the most technically mature and commercially scaled battery technology. Despite this, they have several drawbacks, including the scarcity of required raw materials, safety concerns, capacity degradation over time, and relatively high costs. In some cases, redox flow batteries may offer an attractive alternative. They rely on less scarce materials, are not flammable, do not suffer from capacity loss, and have a lower levelized cost of storage. This technology is particularly effective for providing flexibility over longer periods, ranging from several hours to multiple days. However, this study focuses on lithium-ion batteries to keep the scope manageable, and because all current battery applications in the Netherlands involve this technology [86].

Electricity Market

The model simulates the electricity market using historical hourly wind profiles from [87], combined with Dutch day-ahead prices and electricity demand data from ENTSO-E [88]. As outlined in Section Electricity Market Design, the Dutch electricity market operates through various mechanisms, including bilateral contracts and wholesale trading platforms. In this model, supply is assumed to always meet demand: surplus wind power may be curtailed, and shortages are priced at the value of lost load (VoLL), representing the economic cost of unserved electricity [89].

The model includes three electricity pricing mechanisms:

- Power Purchase Agreements (PPAs) – fixed-price contracts between offshore wind generators and electrolyzers. However, PPA electricity can also be resold on the day-ahead market.
- Day-Ahead (DA) market prices – used for wholesale trading.
- Value of Lost Load (VoLL) – applied when there is insufficient electricity supply.

Although other markets (e.g., intraday, balancing) may offer different insights, they are not included in this study due to the high price uncertainty and their limited impact on the competitiveness between domestic hydrogen production and hydrogen imports. Therefore, only the day-ahead market is considered.

Large-scale batteries are included as flexibility providers. They do not generate power but shift it over time by charging when prices are low and discharging during high prices or shortages. In practice, batteries typically bid at their opportunity cost to maximise profit [26]. However, in this model they are not profit-driven but instead aim to reduce renewable energy curtailment and mitigate price volatility, ultimately contributing to lower overall system costs.

Electricity Demand

In the model, electricity demand is divided into three categories, each with a distinct pattern: Electrolysis, HIC Rotterdam, and Hinterland.

1. Electrolysis demand depends on the availability of offshore wind and high-voltage grid electricity, as well as the competitiveness with imported hydrogen. If no surplus electricity is available and imports are cheaper, the model opts for hydrogen imports over local production.
2. HIC Rotterdam represents local electricity demand within the port. For simplicity, only demand within the port area is considered. Although in reality, surrounding areas such as Rotterdam city and South Holland also contribute significantly, so these are included in the hinterland demand.
3. The hinterland includes electricity demand from the rest of the Netherlands that flows through the Port of Rotterdam. This is approximated as a scale factor (0.275 or 0.1375) of total national demand, based on [86] assumptions and ENTSO-E [88] data.

Although electricity demand for both HIC Rotterdam and the hinterland could be further disaggregated into sectors such as built environment, transport, industry, agriculture/ICT/energy, and flexible demand as defined in the Netbeheer Nederland [46] scenarios, this is not done due to model simplicity, and limited impact on the main conclusions. The focus remains on system-level flows rather than sector-specific demand flows.

4.1.2 Hydrogen System

To simplify the hydrogen system and focus on domestic green hydrogen production, the model includes three main flows: green hydrogen from large-scale electrolysis, imported hydrogen via green ammonia shipments, and hydrogen inflow/outflow from a salt cavern storage facility. Given the high uncertainty around the future hydrogen system, this study assumes a future hydrogen demand in the Port of Rotterdam area [3], [11], focusing specifically on the contribution of green hydrogen. To avoid the added complexity and market price volatility associated with grey, blue, and by-product hydrogen [90], these alternatives are excluded from scope.

As a result, the model assumes a fully green hydrogen system and evaluates flows based on levelized costs of green hydrogen (LCOH) projections rather than fluctuating market prices [19], [27], [51]. Unlike the electricity system, no hydrogen market module is included, relying on cost projections allows a more stable and transparent comparison between domestic production and imports. Although, also on the hydrogen side supply is assumed to always meet

demand: surplus hydrogen may be withdrawn, and shortages are priced at the same value of lost load (VoLL) as electricity representing the assumed economic cost of unserved hydrogen. The hydrogen flows are allocated to two main consumers: HIC Rotterdam and the hinterland. The next sections explain in more detail which system components are included or excluded from the model.

Hydrogen Production

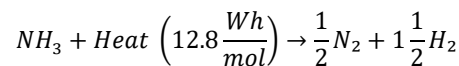
In this model, hydrogen is assumed to be produced exclusively via onshore electrolysis, reflecting current technological maturity and infrastructure availability in the Port of Rotterdam area [63]. Offshore electrolysis, where hydrogen is produced directly at sea near wind farms, is not included. Although studies such as [91], [92] suggest it become economically viable in the longer term and offer advantages like reduced offshore grid congestion, lower transmission losses, and closer coupling with offshore wind generation, its development is still highly uncertain. High capital costs, technical complexity, and the lack of commercial deployment make it unsuitable for near-term analysis. This is supported by already high levelized costs of onshore electrolysis [27], and expert insights suggesting that offshore electrolysis is not a near-term priority for the Port of Rotterdam [93].

Blue, grey, and by-product hydrogen are also excluded. Although currently part of the Dutch hydrogen mix [11], [19], these routes are omitted to maintain a clear focus on a fully green hydrogen system. Including them would introduce market price variability and shift the study's scope from renewable integration to broader hydrogen market modelling, which falls outside the aim of this analysis.

Hydrogen Import

As outlined in Section Green Hydrogen Import, hydrogen can be imported via four main pathways: pipelines, liquefied hydrogen, LOHCs, and ammonia. This study considers only ammonia-based imports, as ammonia is currently the most established and widely used hydrogen carrier in the Port of Rotterdam (PoR) [23]. Furthermore, in PoR's Connected Deep Green (CDG) scenario—focused on full renewable energy system integration—ammonia is projected to represent between 85% (by 2030) and 65% (by 2050) of all imported hydrogen derivatives [94].

Ammonia is modelled as arriving by ship, with costs including production and shipping (see Section Hydrogen Import). Additional storage and cracking costs are accounted for, while alternative ammonia uses—such as direct combustion or industrial feedstock—are excluded to maintain the focus on hydrogen conversion. Cracking ammonia to hydrogen follows the reaction [68]:



This process requires high-temperature heat. To avoid CO₂ emissions, Fluor [23] recommends using tail gas and parasitic ammonia combustion instead of carbon-based fuels. However, it should be noted that this method is relatively inefficient, achieving a thermal efficiency of 68.5%, and is associated with high NO_x emissions [95].

Electric crackers offer a cleaner alternative, avoiding combustion-related emissions altogether and enabling full electrification. According to Fluor [95], they are expected to achieve slightly higher efficiencies (up to ~75%) with lower operating emissions. However, they are excluded from this study due to their low Technology Readiness Level (TRL) and limited scalability at present [96].

Hydrogen Storage

As described in Section Energy Storage, hydrogen can be stored in various ways. Given the focus on high-volume storage in this study, only underground hydrogen storage is considered, specifically in salt caverns, rather than above-ground or small-scale solutions.

According to TNO et al. [38], onshore salt caverns are the most cost-effective option for both short-cycle storage (ranging from hourly to biweekly injection/withdrawal) and seasonal storage (weekly to monthly). While depleted gas fields offer comparable benefits for long-term strategic reserves (e.g. in case of international supply disruptions), salt caverns are better suited for operational flexibility and frequent cycling, making them the preferred option for this study's focus on hourly system balancing.

Hydrogen Demand

In the model, hydrogen demand is divided into two categories, each with a fixed demand pattern:

1. HIC Rotterdam, which represents local hydrogen within the port. For simplicity, only demand within the port area is considered. Although in reality, surrounding areas such as Rotterdam city and South Holland also contribute significantly, so these are included in the hinterland demand.
2. Hinterland, which includes hydrogen demand from the rest of the Netherlands and neighbouring countries that flows through the Port of Rotterdam. This is approximated as a multiply factor of the HIC Rotterdam demand, based on the CDG scenario [94].

Hydrogen demand for both HIC Rotterdam and the hinterland could be further disaggregated into sectors such as built environment, transport, industry, agriculture/ICT/energy, and flexible demand as defined in the Netbeheer Nederland scenarios [46]. However, this is not done due to model simplicity and its limited impact on the main conclusions. The focus remains on system-level flows rather than sector-specific demand flows.

4.2 Specification

To specify how system performance is measured and how interactions between uncertainties, policy choices, and system behaviour are structured in the model, two key elements are presented. First, a set of Key Performance Indicators (KPIs) is defined to evaluate outcomes under different scenarios. Second, the specification is structured using the XLRM framework, which captures the relationships between external factors, levers, system dynamics, and resulting performance (KPI) outcomes.

4.2.1 Key Performance Metrics

To assess system performance, a set of quantifiable Key Performance Indicators (KPIs) is defined. These are aligned with the four pillars of energy security (Availability, Accessibility, Acceptability, and Affordability) as introduced in Section Evaluation by 4 A's of Energy Security. The following indicators per A are selected:

Availability:

- **Expected Energy Not Served (EENS) [GWh/year]**. EENS quantifies the volume of (electricity + hydrogen) demand that remains unmet due to capacity shortages. A lower value reflects the system's ability to maintain supply under stress. As defined by ACER, EENS is a core metric for evaluating supply adequacy [89].
- **Loss of Load Expectation (LOLE) [hours/year]**. LOLE indicates the expected number of hours per year during which demand exceeds available capacity, resulting in shortages. Here too, a lower value reflects the system's ability to maintain supply under stress. Alongside EENS, it provides insight into the frequency of reliability events [89].

Accessibility:

- **Domestic Electrolyser H2 Share (H2-E Share) [-]**. This metric measures the share of total hydrogen demand supplied by domestic production (via electrolyzers) rather than imports. A higher rate indicates greater use of local resources and hydrogen infrastructure, reducing reliance on external supply chains and improving system accessibility and autonomy.

Acceptability:

- **Average CO2 Emissions System (Avg. CO2) [ton CO2/GWh]**. This metric reflects the average carbon intensity of the energy used to fulfil demand (electricity + hydrogen). A lower value indicates better environmental performance, as it means a higher share of wind electricity in both the hydrogen (via domestic production) and electricity systems. It captures the environmental performance of the whole system.

Affordability:

- **Levelized Costs of H2 (LCOH) [€/kg H2]**. LCOH expresses the total lifetime cost of hydrogen production per unit of energy. It is a standard economic benchmark widely used, [3], [27], [97], to assess cost competitiveness between domestic and imported hydrogen.
- **Full Load Hours (FLH) [hours/year]**. FLH represents the number of hours per year (ideally 8760) that electrolyzers or ammonia crackers would need to operate at full capacity to produce their actual annual output. It is a key indicator of asset utilisation and economic efficiency [89]. Higher FLH values indicate more effective use of capital-intensive infrastructure, enabling better CAPEX recovery and lower hydrogen production costs per unit of energy.
- **Average System Costs (Avg. SC) [M€/GWh]**. This metric aggregates all system-level costs, including investments, operational expenses, imports, and tariffs, relative to the total energy demand (electricity + hydrogen). It enables high-level comparison of economic performance across different scenarios.

4.2.2 XLRM of the Research

Based on the conceptualisation presented in the previous sub-paragraphs, the model is structured using the XLRM framework (as explained in Section XLRM Framework). Figure 4-5 below provides a summary of the key variables within the model, while a more detailed version can be found in Appendix C.

On the left side, external factors represent exogenous uncertainties, which are used in the scenario design to explore their impact on system performance. On the right side, performance metrics—as described in Section 4.2.1—are used to quantify system outcomes. In between, policy levers represent possible interventions available to decision-makers, allowing them to influence the system’s behaviour. Lastly, relationships in the system refer to the objective function and set of linear constraints, which together define the internal logic and operational structure of the model.

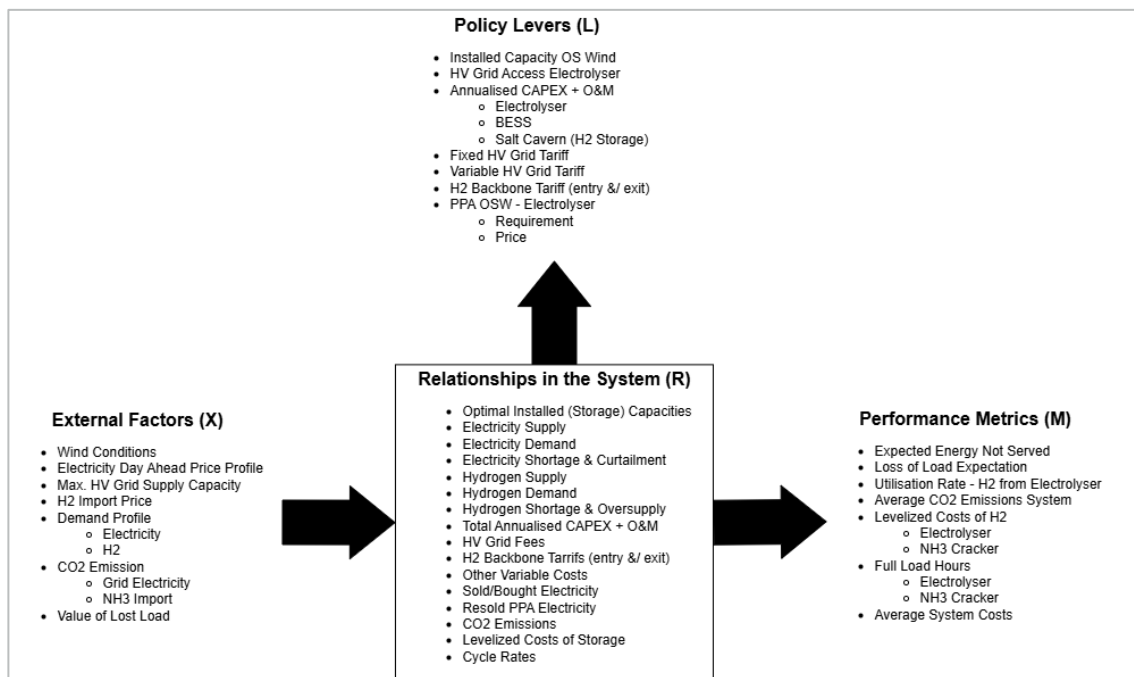


Figure 4-5: XLRM of the Research

4.3 Main Takeaways on Conceptualisation and Specification

In summary, this chapter has outlined the conceptual model and defined the scope, assumptions, and system boundaries used to represent the electricity and hydrogen landscape in the Port of Rotterdam. By simplifying complex market dynamics and infrastructure into a scenario-based framework, the model enables robust analysis of hydrogen supply strategies under varying techno-economic conditions. The selected KPIs and XLRM structure provide a clear foundation for the implementation phase presented in the following chapter.

5 Implementation

Building on the conceptualisation and specification outlined in Chapter 4, this chapter focuses on the implementation phase of the modelling & simulation life-cycle. It explains how the conceptual model is implemented into a simulation model in Linny-R. The chapter introduces key Linny-R modelling concepts, explains the structure of the model including its main clusters and relationships, and outlines system choices. It then details the model settings, input data, and core formulas used to determine Levelized Costs. The chapter concludes with a discussion on the model verification, ensuring consistency, correctness, and alignment with the intended system behaviour.

5.1 Key Concepts of Linny-R

As introduced earlier in Section Modelling Tool - Linny-R, Linny-R is a modelling environment that uses a set of conceptual building blocks to represent production systems. Each block is adjustable, can be uniquely named, and can be used in equations, simulations and visualisations over a defined time series. Collectively, these named entities serve as the basis for constructing a Linny-R model. This model enables accurate analysis, experimentation, and communication of a complex system, such as the electricity and hydrogen system of HIC Rotterdam. The main entities relevant to this study are described in the following sections [77].

- A **process** in Linny-R transforms input products into output products (e.g. the generation of wind electricity through offshore wind). Each process must connect to at least one product and can optionally be assigned to an actor to denote ownership. Its operation is limited by lower-and-upper bounds (LB, UB) and the optimal production level (L) is calculated per time step. Initial levels (IL) can be set. If market prices apply, cash flow (CF) is computed as inflows (CI) minus outflows (CO). With cost inference enabled, a cost price (CP) is assigned.
- A **product** represents a resource, physical (e.g. electricity) or informational (e.g. market signals), that can be produced or consumed by processes. Data products are shown with dashed outlines. As a result of these production and consumption processes, product levels (L) change during simulation and are bounded (LB, UB) with optional initial levels (IL). Products may have a defined price (P) and, if cost inference is active, a cost price (CP) and highest cost price (HCP).
- An **actor** denotes ownership of processes and organizes financial flows. Cash flow (CF) equals the sum of CF from all owned processes, with aggregated inflow (CI) and outflow (CO). Actors can be weighted (W) to prioritize objectives, with a default weight of 1.
- A **link** defines a potential flow of products or data between entities. A link from a product to a process indicates consumption, while one from a process to a product indicates production. The process level and the link rate determine the flow (F). Dashed links represent data flows to data products and convey specific numerical multipliers, such as peak increase (Δ), about a process or product. These data flows do not affect source levels. Cost shares (SOC) can allocate process costs to outputs.
- A **constraint** is a curved arrow connecting two nodes and represents a piecewise-linear relationship. Constraints link system behaviour logically.
- A **cluster** groups processes into hierarchical structures for better organization. Each process can belong to only one parent cluster. Clusters do not affect model optimization directly but can be associated with actors for structural clarity. When simulations run, Linny-R aggregates cash flow (CF), inflow (CI), and outflow (CO) across all processes and nested clusters. Unit balances within clusters can also be tracked to evaluate internal flows.
- A **dataset** contains numeric values, often as a time series. Values are indexed absolutely and can be wrapped if they are periodic. Datasets feed external data, such as demand or day-ahead prices, into the model.
- An **equation** is a reusable, named expression that can be referenced in other formulas or annotations throughout the model. Equations improve modularity and clarity, enabling the reuse of complex logic.

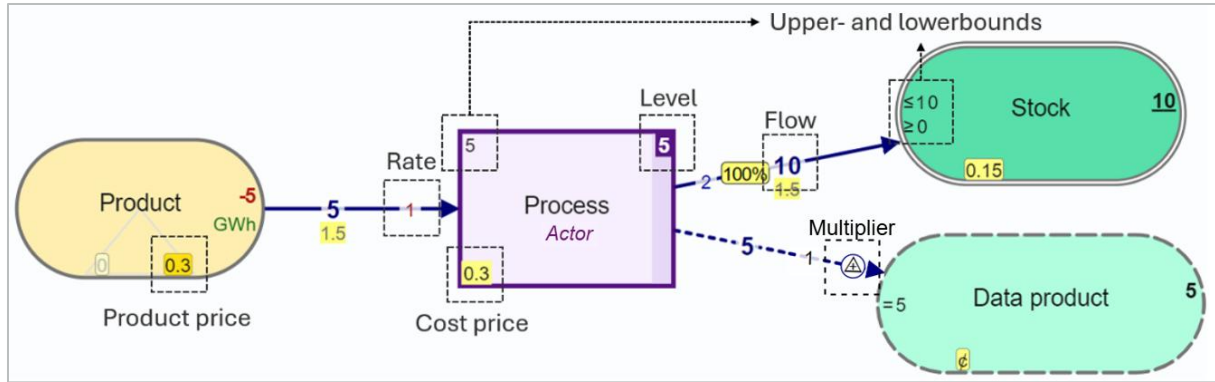


Figure 5-1: Linny-R - Key Concepts (adapted from [84])

5.2 The Model

Figure 5-2 below presents a top-level overview of the Linny-R model, outlining the different clusters involved in the electricity and hydrogen system of the Haven Industrieel Complex (HIC) in Rotterdam. Each cluster is described in more detail in the following subsections. The general assumptions applicable to the entire model are as follows:

- In line with the SDE++ Eindadvies Basisbedragen [98], all hydrogen flows in the model are expressed in GWh on a higher heating value (HHV) basis, using: 1 kWh HHV = 0.0254 kg H₂ and 1 kg H₂ = 39.32 kWh HHV (Hence, 1 GWh HHV = 25.4 ton H₂ and 1 ton H₂ = 0.03932 GWh HHV. This standardisation ensures consistency within the system of both electricity and hydrogen.
- The entire HIC area is modelled as a single node, also called a “copper plate”, implying that electricity and hydrogen can flow freely within the region without congestion or transport losses.
- The model runs on hourly resolution over a one-year horizon, assuming full foresight (perfect knowledge of future conditions), allowing for fully optimised dispatch and investment planning.
- Demand for both electricity and hydrogen is always met. Shortfalls are covered by back-up supply from TenneT or Gasunie, priced at the Value of Lost Load (VoLL), penalising unmet demand with high system costs.
- All offshore wind and HV grid electricity are assumed fully deliverable to HIC, regardless of external congestion. Hourly surplus wind is curtailed. Surplus hydrogen is withdrawn by Gasunie (assumed to be consumed elsewhere in the backbone).
- The electricity from the HV grid is assumed to consist of at least 90% renewable electricity and can therefore, as discussed earlier in Section European Union Hydrogen Policy, be used to produce ‘green’ hydrogen under REDIII.
- The model minimises total system costs across all actors and time steps. This may come at the expense of individual actors' profits, as strategic bidding and profit maximisation are not modelled.
- Day-ahead electricity prices from 2024 are used as a proxy for future market prices. This is a limitation, as future price dynamics, especially with increased wind penetration, may differ.
- All prices are adjusted to constant EUR2025, based on inflation indexing [99].
- Supply and demand for electricity and hydrogen are aggregated at HIC Rotterdam and hinterland level. Site-specific spatial or technical constraints are excluded.
- Technical characteristics such as ramping limitations, start-up times, and minimum load levels are not modelled. This simplification allows for a clearer focus on system-level trade-offs.
- Capital investment decisions are only modelled for electrolysis, Battery Energy Storage Systems (BESS), and hydrogen storage. Other investment decisions depend on factors such as required HV Grid / Backbone connection capacity. CapEx and O&M costs are pre-calculated using formulas detailed in Section 5.4
- Hydrogen imports (NH₃ cracking) and electricity from the high-voltage grid are scaled automatically to cost-efficiently meet any demand.

- CO₂ emissions are tracked only for hydrogen imports (based on RED III methodology [51]), and HV Grid electricity consumption (using the forecasted average CO₂ intensity of the Dutch grid [83]). Emissions from materials (e.g. equipment) or infrastructure are excluded.
- Carbon pricing is not included in the model. This decision is based on the assumption that the objective is to assess techno-economic performance under fixed system cost conditions rather than to simulate market behaviour or regulatory instruments.

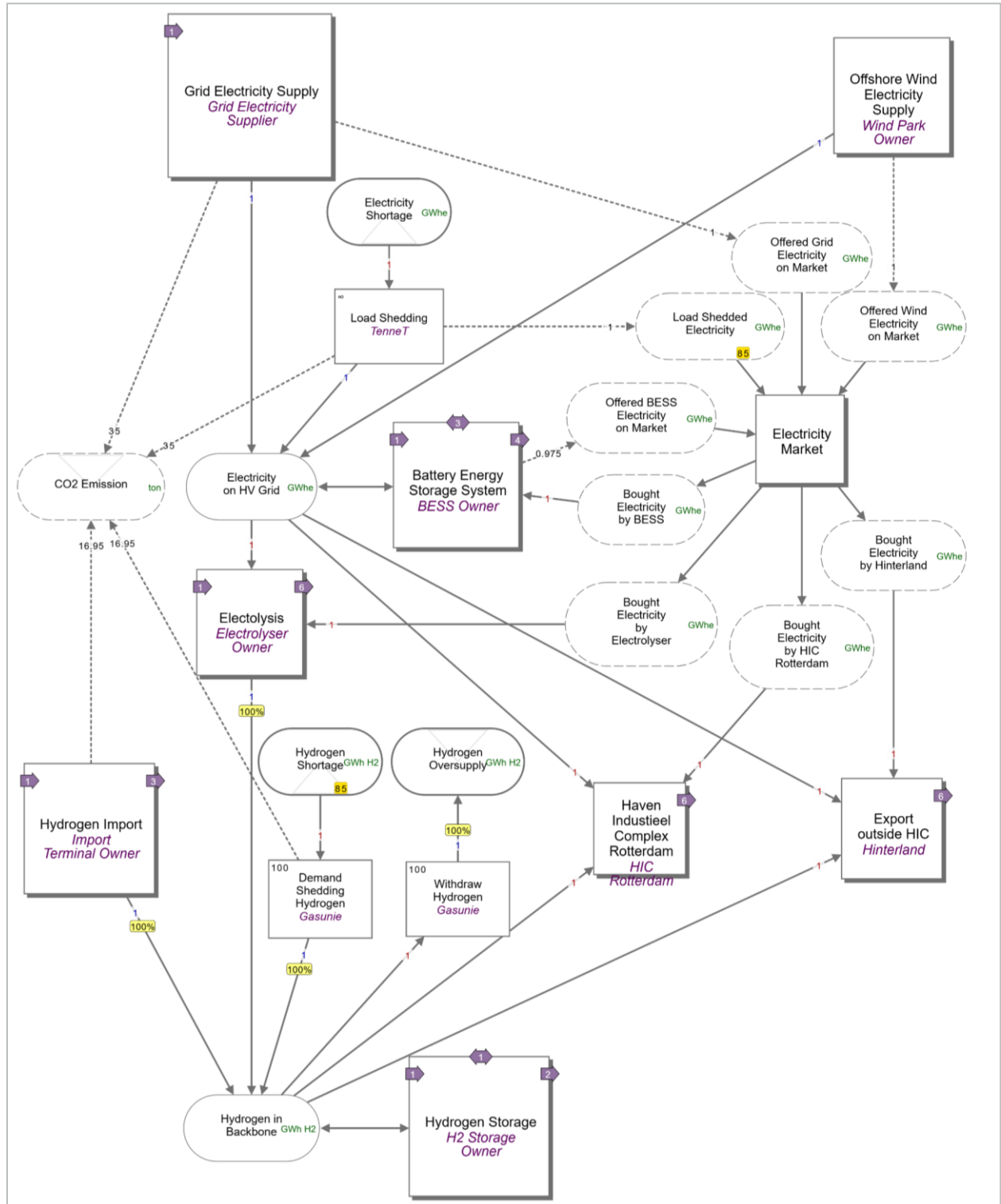


Figure 5-2: Linny-R - Top-Level model

5.2.1 Electricity Supply

Electricity supply is divided into two clusters, as shown in Figure 5-3: Grid Electricity Supply (left), and Wind Electricity Supply (right). The assumptions applicable to these clusters are as follows:

- Grid electricity supply is considered unlimited within the model, except for an upper bound constraint represented by the process “Connect Grid Electricity with HV Grid”, which reflects the available net transport capacity for importing and exporting electricity to and from the high-voltage (HV) grid. According to DNV (2025) [56], the Port of Rotterdam is connected to the Dutch HV grid via three 380 kV substations: Maasvlakte, Europoort, and Simonshaven. Maasvlakte is linked to both Europoort and Simonshaven, which in turn connect to stations in the hinterland. Each connection is assumed to consist of two 2.5 GW lines, resulting in a total gross transport capacity of 10 GW between HIC Rotterdam and the surrounding regions. Applying a N-1 reliability criterion of DNV, which guarantees grid stability if one component fails, the net available HV grid capacity is conservatively assumed to be 5 GW in the base case.
- The physical flow of grid electricity is connected to the HV grid. The same quantity contributes to informational flows to CO₂ emissions, and to the electricity market, where it is priced at the day-ahead (DA) market rate.
- Offshore wind electricity supply is based on a fixed installed capacity within the process “Generate Offshore Wind Electricity”, with an hourly generation output calculated by multiplying this capacity by a capacity factor derived from a historical wind year.
- In the case of oversupply, surplus wind electricity is curtailed via the “Curtail Wind Electricity” process.
- Wind electricity is physically connected to the HV grid via the process “Connect Wind Electricity with HV Grid”. The corresponding volume is also included in informational flows to the electricity market, where it is priced either via the day-ahead market or through a Power Purchase Agreement (PPA).
- Electricity suppliers are not linked to costs or investment decisions in the model. Therefore their weight of their cash flow in the objective function is set to 0 in Linny-R, excluding it from system cost minimisation. They make no investment decisions, incur no costs, and have no economic incentives—their sole role is to ensure electricity availability, without engaging in sales or cost recovery. While grid and wind electricity are priced within the Electricity Market cluster and contribute to system costs, these are not treated as cash flows for the suppliers. The Wind Park Owner is assigned a near-zero weight (0.00005) to ensure wind electricity is used preferentially, avoiding curtailment when grid electricity would otherwise be imported simultaneously.

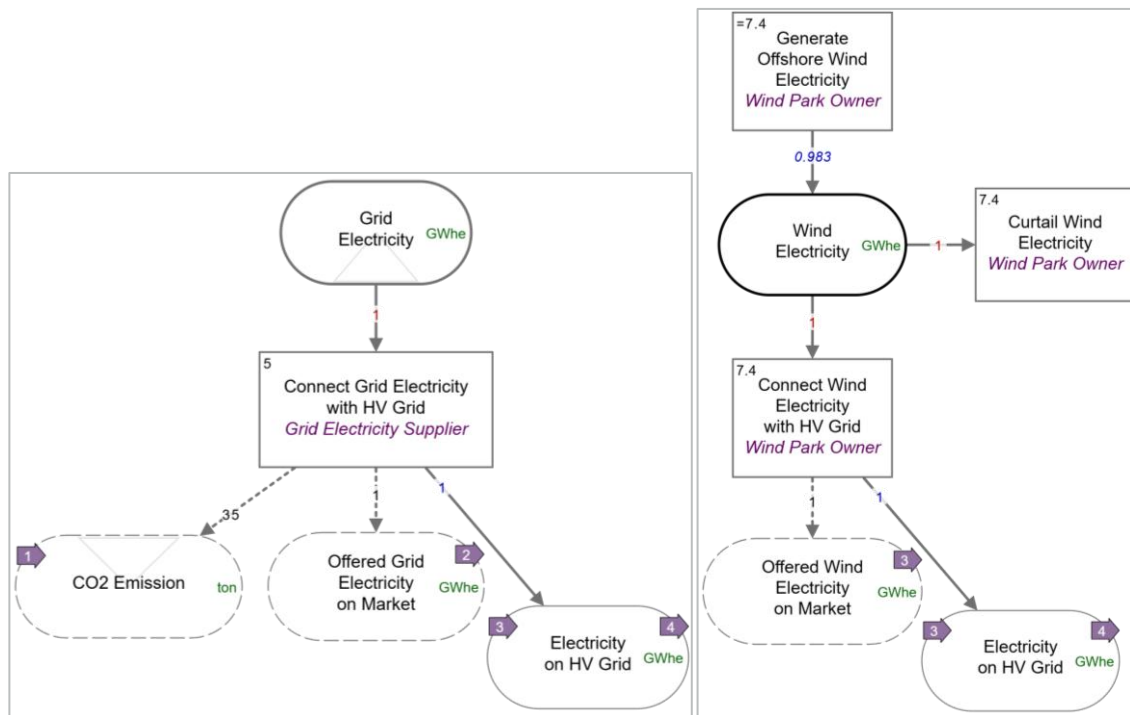


Figure 5-3: Linny-R - Electricity Supply Clusters (Grid Electricity left & Wind Electricity right)

5.2.2 Battery Energy Storage System (BESS)

As outlined in Section Electricity Storage, this study focuses on large-scale electricity storage using lithium-ion batteries. Electricity storage is modelled as a single cluster, shown in Figure 5-4, with the following key assumptions:

- A 4-hour system is assumed, meaning the BESS can charge or discharge up to 25% of its total storage capacity per hour.
- Electricity is physically transferred from the high-voltage (HV) grid to the BESS via the process “Charge BESS”, and discharged back through “Discharge BESS”. The corresponding charge and discharge volumes are also included in informational flows to the “Electricity Market” cluster, where electricity is traded at day-ahead market prices. Additionally, the BESS is initially charged via the “Initial Fill BESS” process, dependent on a parameter. This electricity is priced at average day-ahead level.
- The BESS can both buy and sell electricity in the Electricity Market cluster. However, strategic bidding is not modelled; dispatch is based solely on system cost minimisation.
- The following technical assumptions apply:
 - Round-trip efficiency is set at 95%.
 - Self-discharge and battery degradation are excluded for simplification.
 - There is no minimum discharge rate.
- Connection CAPEX and BESS CAPEX are modelled as separate investment decisions to cost-effectively incentivize both charge/discharge rate as electricity storage capacity.

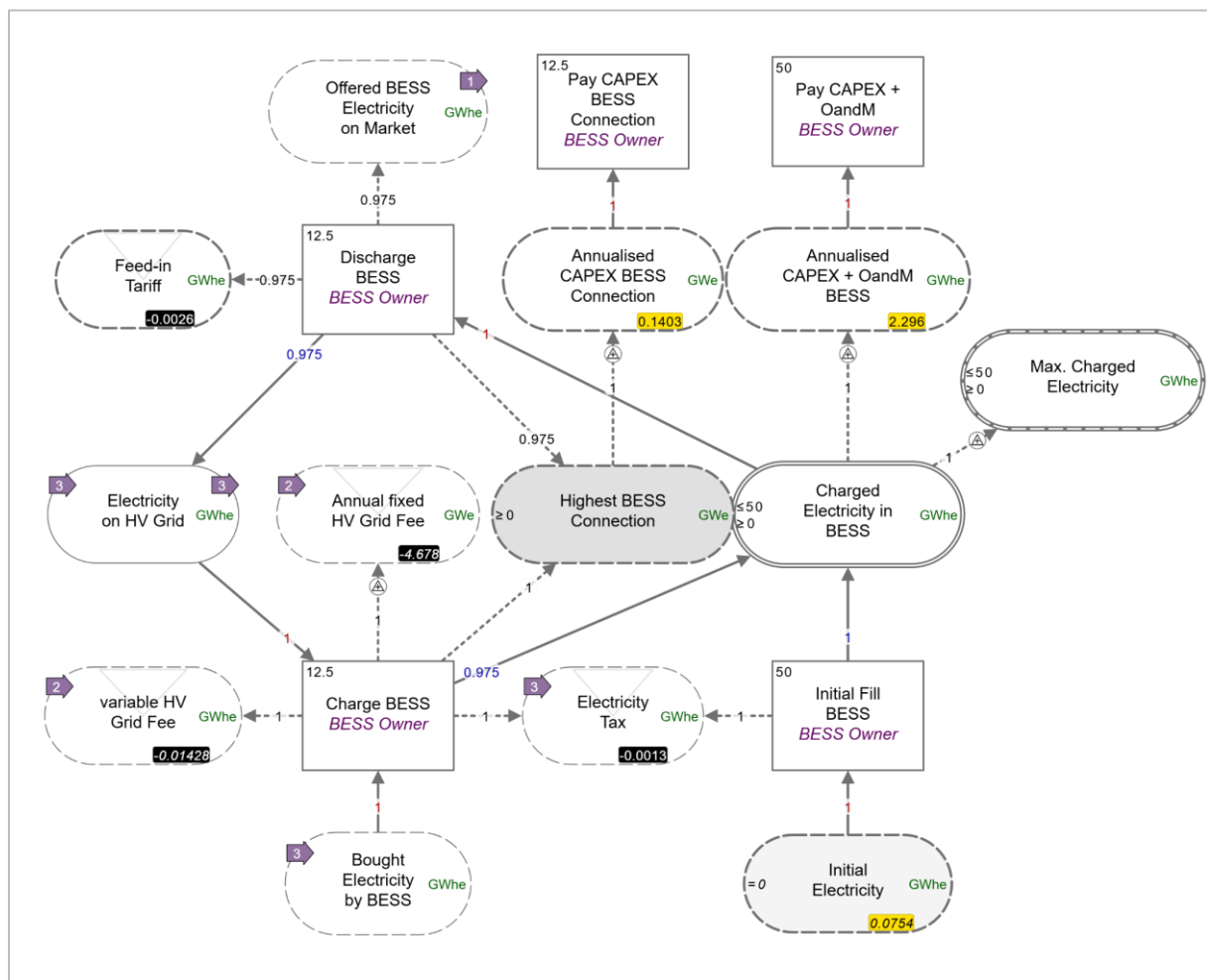


Figure 5-4: Linny-R - Battery Energy Storage System (BESS) Cluster

5.2.3 Electricity Market

As outlined in Section Electricity Market, the electricity market in the model prices electricity through three mechanisms: Day-Ahead (DA) Market, Power Purchase Agreement (PPA) between the Offshore Wind Park and the Electrolyser, and Value of Lost Load (VoLL). The market is modelled as a single cluster, shown in Figure 5-5, with the following main assumptions:

- The market starts on top with informational flows of electricity offered by the following actors: BESS Owner, Grid Electricity Supplier, and Wind Park Owner.
- Grid and BESS electricity is sold to the following consumers at the hourly DA price: Electrolyser, BESS, HIC Rotterdam, and Hinterland. Wind electricity is sold via DA market to Electrolyser, BESS, HIC Rotterdam, and Hinterland; and sold via PPA exclusively to the Electrolyser.
- The Electrolyser is obligated to consume wind electricity via the PPA based on the PPA requirement parameter (0-100%), which is a percentage of the hourly generated wind electricity.
- 100% of the contracted PPA electricity can be resold on the DA market to other consumers (BESS, HIC Rotterdam, or Hinterland). Any profit or loss from this resale is included in the electrolyser's Levelized Costs of Hydrogen (LCOH) Calculation.
- In addition to PPA electricity, the Electrolyser can purchase additional electricity via the DA market dependent on the Electrolysers' maximum HV grid access parameter. To keep the right size of order, the maximum HV grid access parameter is scaled at 0-100% of the installed OSW capacity.
- In case of a supply shortage, electricity demand is met via load shedding, priced at the Value of Lost Load (VoLL) at the bottom of the cluster.

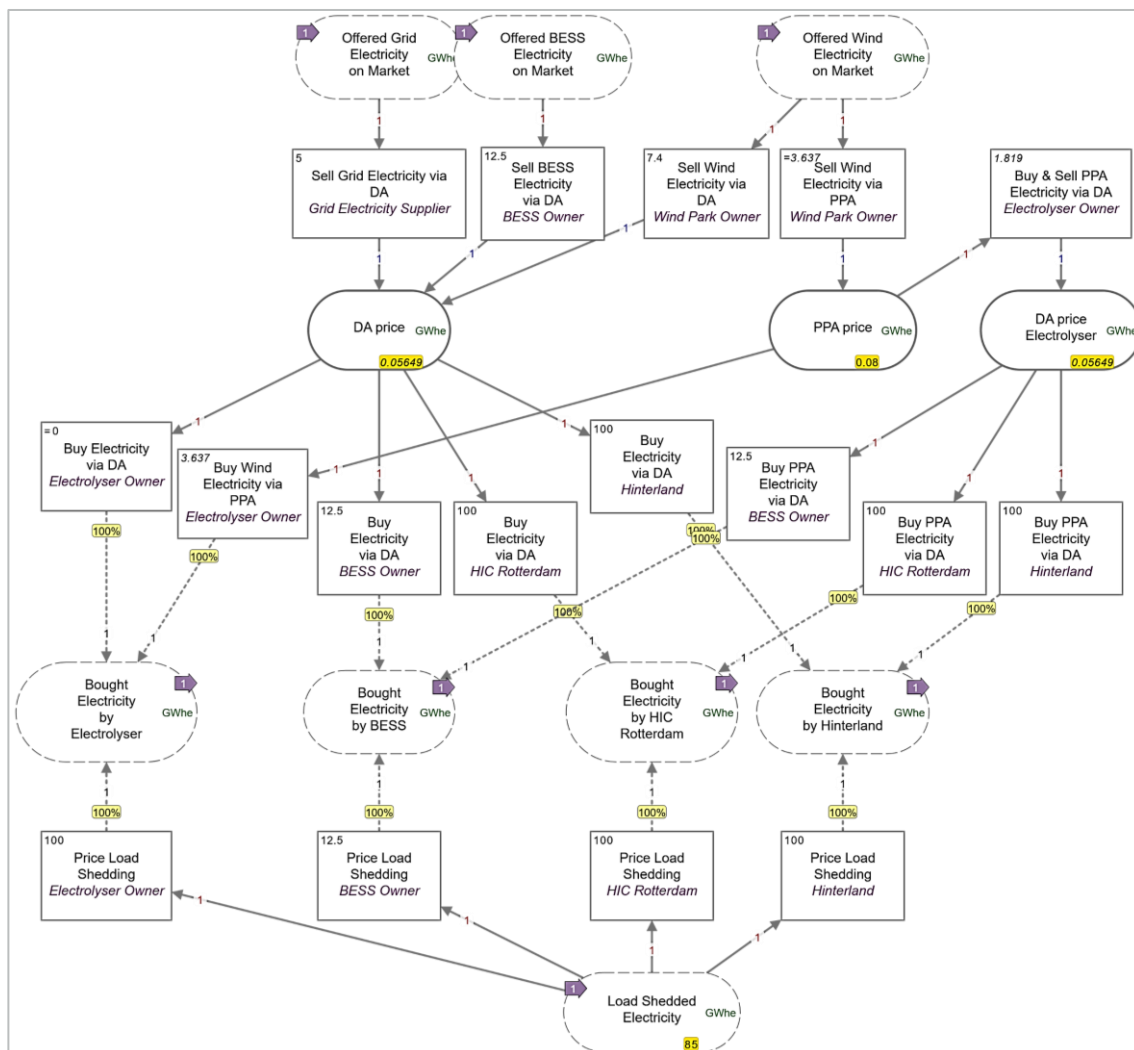


Figure 5-5: Linny-R - Electricity Market Cluster

5.2.4 Electrolysis

As outlined in Section Hydrogen Production, this study considers only domestic hydrogen production via onshore electrolysis. Electrolysis is modelled as a single cluster, shown in Figure 5-6, with the following main assumptions:

- Only electricity feedstock costs are considered in the electrolysis process. Raw water costs and potential revenues from oxygen or waste heat are excluded from the model.
- The electrolysis process starts with the physical flow of electricity from the HV grid to the electrolyser. At the same time, informative cost flows, including electricity taxes, annual fixed and variable grid fees and electricity market procurement costs, are added in the “Usage Electricity by Electrolyser” process.
- In the “Electrolyse Onshore” process, the investment decision for installed capacity is made based on annual CAPEX and O&M costs. The green hydrogen produced is then transferred through the “Transfer Green Hydrogen to Backbone” process, where it becomes available to end-users.
- The installed capacity is expressed in GW electric (GWe). Therefore, KPIs such as Full Load Hours (FLH) and Levelised Cost of Hydrogen (LCOH) are calculated on the basis of output (hydrogen flow) rather than electricity input.

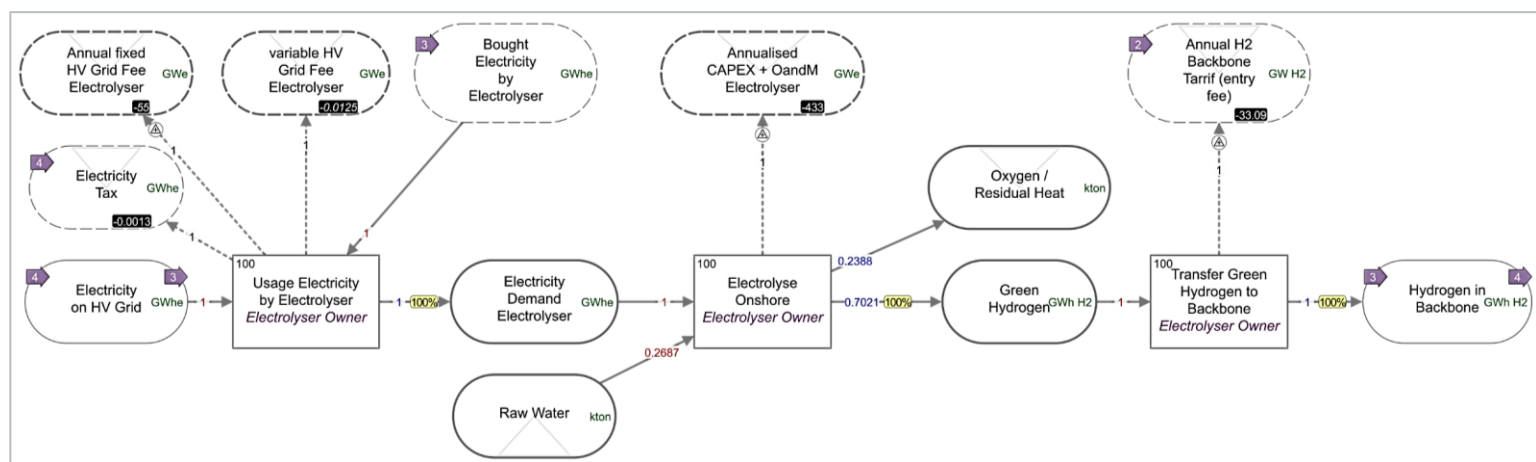


Figure 5-6: Linny-R - Electrolysis Cluster

5.2.5 Hydrogen Import

As outlined in Section Hydrogen Import, this study considers hydrogen import exclusively via shipped green ammonia (NH₃). The hydrogen import process is modeled as a single cluster, illustrated in Figure 5-7, with the following main assumptions:

- As described at the start of Section 5.2, all hydrogen flows are expressed in GWh (HHV). Consequently, ammonia imports are represented in terms of their hydrogen content, rather than in physical units such as tonnes of NH₃. This approach, consistent with methodologies used in multiple studies [19], [51], [98], enables direct comparison with domestic hydrogen production via electrolysis.
- The model includes only the following cost components: ammonia feedstock cost, storage and cracking cost, and hydrogen backbone transport tariff. These are modelled as fixed hourly costs, inclusive of CAPEX depreciation and O&M. Revenues from by-products (e.g., nitrogen) and energy consumption for cracking and storage (e.g., compression, heating) are excluded from physical flows but assumed to be reflected in the above cost assumptions.
- The process begins with “Store & Crack NH₃ to Hydrogen”, where the incoming physical flow of “Shipped Green NH₃” (priced via the “Shipped Green NH₃ Price” parameter) is converted into cracked hydrogen and nitrogen. Associated CO₂ emissions of the NH₃ supply pathway are included as informational flows.
- NH₃ supply and cracker capacity are assumed to be unlimited, scaling cost-efficiently to meet residual hydrogen demand not met by domestic electrolysis.
- The cracker and electrolyser are perfectly aligned to jointly meet total hydrogen demand.

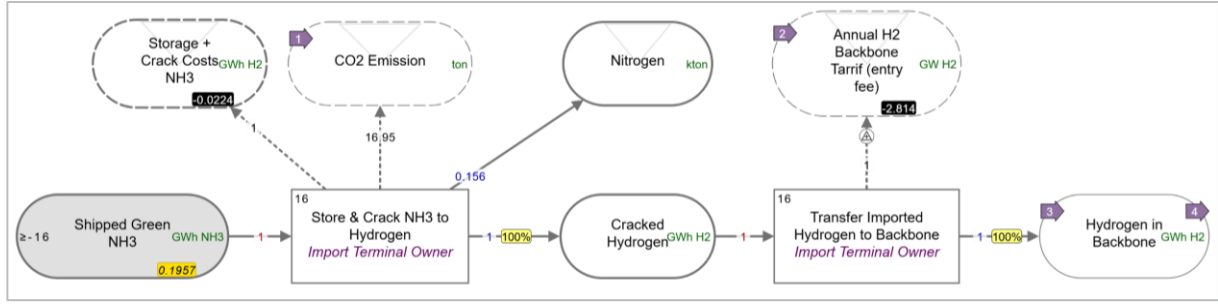


Figure 5-7: Linny-R - Hydrogen Import Cluster

5.2.6 Hydrogen Storage

As outlined in Section Hydrogen Storage, this study considers only hydrogen storage exclusively via onshore Salt Caverns. Hydrogen storage is modelled as a single cluster, shown in Figure 5-8, with the following main assumptions:

- Hydrogen storage is based on a gross capacity of 250 GWh, representative of salt cavern sites such as Zuidwending in Drenthe [38]. The model includes specific inflow/outflow constraints, as well as defined technical and cost characteristics.
- Physical hydrogen flows from the backbone enter the storage cluster through the “Store Hydrogen” process, are stored in the “Stored Hydrogen in Salt Cavern” product, and are later retrieved via the “Destore Hydrogen” process, re-entering the backbone. Additionally, the salt cavern is initially charged via the “Initial Fill Salt Cavern” process, dependent on a parameter. This hydrogen is priced at import level.
- Costs are assigned through three components, which drive the investment decision: an entry fee for hydrogen entering the backbone, an exit fee for hydrogen withdrawn from the backbone, and annualised CAPEX and O&M costs for the storage facility itself.
- The model includes constraints on both the maximum storage capacity and the hourly store/destore rate. These are represented by dotted lines connecting the product “Max. Stored Hydrogen” to the store and destore processes. To represent pressure-based limitations, the model assumes that the hourly capacity is limited to 0.72% of the total volume. This is derived from a maximum allowed pressure variation of 17.28% per day, which means that at full storage capacity (e.g. 500 GWh), the system allows a maximum hourly inflow of 3.6 GWh and a maximum withdrawal rate of 7.2 GWh, assuming a linear relationship between pressure and flow rate.

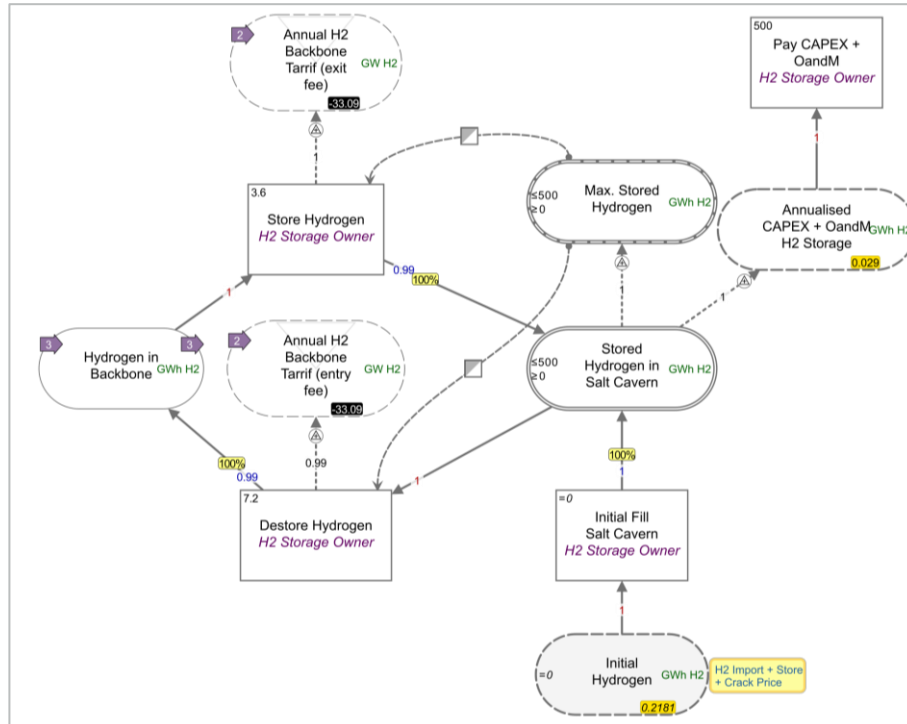


Figure 5-8: Linny-R - Hydrogen Storage Cluster

5.2.7 HIC Rotterdam and Hinterland Demand

As previously described, this study includes energy demand from two key nodes: HIC Rotterdam and the Hinterland. Electricity and hydrogen demand from these nodes is modelled as two separate clusters, illustrated in Figure 5-9. The key assumptions are as follows:

- Electricity Demand:
 - The physical flow of electricity from the HV grid passes through the “Usage Electricity by ...” HIC Rotterdam/Hinterland process.
 - Here, costs such as grid fees, electricity tax, and the electricity price from the Electricity Market cluster are applied. The HV grid fees are divided in a fixed and variable component as further elaborated in Section Variable HV Grid Factor in 5.5.2.
 - The electricity flow ends in the product “Electricity Demand ...” HIC Rotterdam/Hinterland product, which must always be fulfilled, based on a predefined electricity demand pattern from a dataset.
- Hydrogen Demand:
 - The physical flow of hydrogen from the backbone is directed through the “Usage Hydrogen by ...” HIC Rotterdam/Hinterland process.
 - In this process, the hydrogen exit fee is applied.
 - The hydrogen flow ends in the product “Hydrogen Demand ...” HIC Rotterdam/Hinterland product, which also must always be fulfilled, according to a predefined hydrogen demand pattern form a dataset.

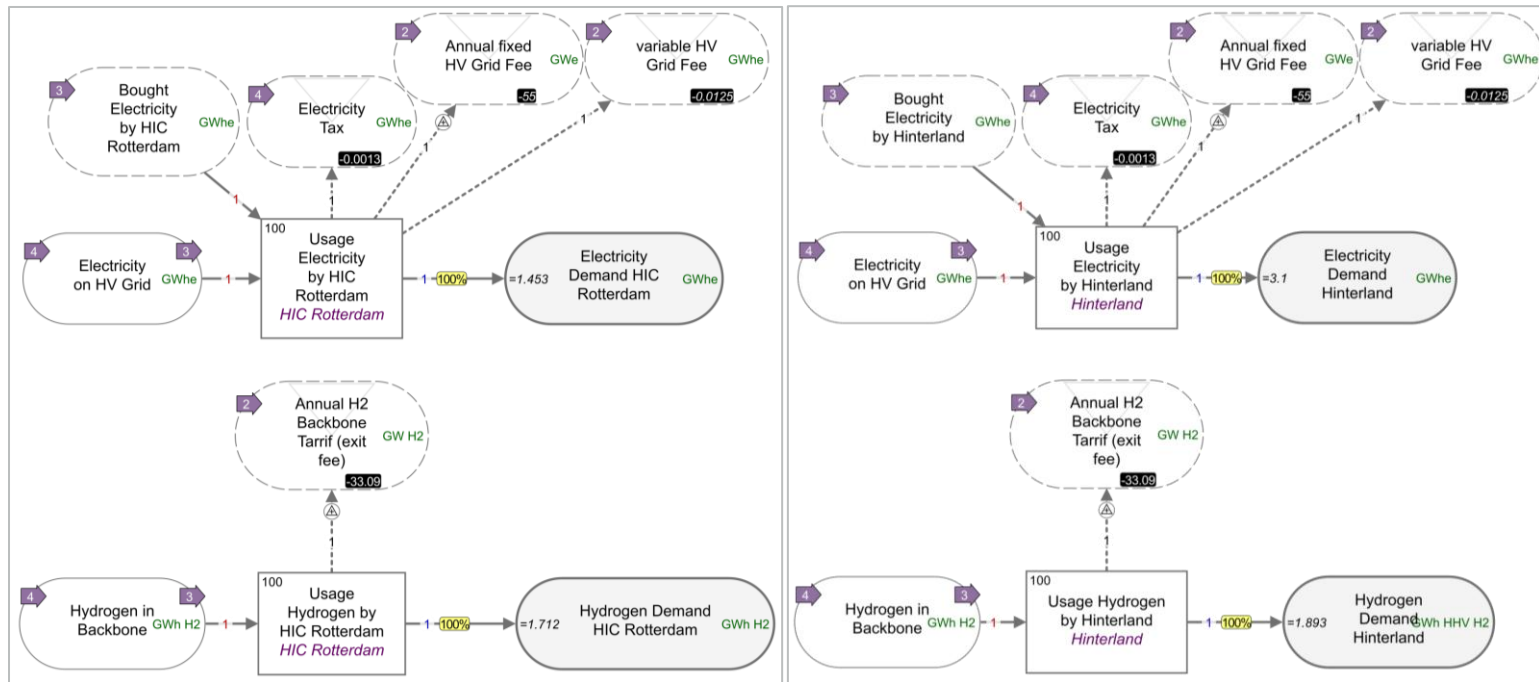


Figure 5-9: Linny-R - HIC Rotterdam (Left) & Hinterland (Right) Clusters

5.3 Model Settings

The Linny-R model is simulated on an hourly basis over a full calendar year, from 1 January to 31 December, resulting in 8760 time steps per simulation run. This setup captures hourly variability in key parameters such as wind capacity factors, day-ahead electricity prices, electricity and hydrogen demand and variable grid fee factors. The model uses a block length of one full year (8784 hours in 2024), meaning the solver optimises in once over the whole year. This avoids the required high computational power of hourly optimisation and allows the model to make cost-efficient long-term decisions within the defined time horizon. The forward-looking parameter is set to 0, meaning the model has no information beyond the current simulation year. However, within this one-year window, the model operates with full foresight, meaning that all hourly input data is known in advance. This approach allows the model to produce a cost-

optimal system configuration, which serves as a benchmark scenario rather than a precise forecast. Given the large uncertainties in long-term energy system projections, such a cost-optimal benchmark is more useful for investigating system behaviour. Moreover, if a system performs well (poorly) under these idealised conditions, it gives strong indications of underlying cost-effectiveness of specific configurations. The base model settings are summarised in Table 5-1 below.

An important reason for using full foresight is the varying predictability of input data. Electricity and hydrogen demand profiles are relatively stable and can be accurately forecasted due to their regular patterns. In contrast, wind conditions are more volatile, although [56] shows that wind capacity factors are generally lower between June and September. Additionally, electricity demand, and thereby variable grid fees, are typically lower during summer months [100]. By using full foresight, these ‘known’ seasonal effects are incorporated and allows the model to respond realistically to temporal shifts in both supply and demand. Without the inclusion of such temporal patterns, the model would behave as if unaware of future variations, potentially resulting in unrealistic system behaviour, such as failing to prepare for seasonal peaks in supply and demand.

Table 5-1: Linny-R - Overview of Base Model Settings

Model Setting	Value
Currency unit	M€
Electricity/Hydrogen unit	GWh
Time step	hour
Optimisation period (t_0 - t_N)	1-8784
Block length	8784
Look-ahead	0
Base historic year	2024

5.4 LCOH Calculations

Below, the cost methodologies for calculating the Levelized Cost of Hydrogen (LCOH) from both domestic electrolysis and hydrogen imports via ammonia, is described. These LCOHs are reported in €/kg H₂, which is standard in hydrogen economics and allows for easier comparison with other studies. All underlying model inputs (e.g., CAPEX, OPEX, grid tariffs) are handled in M€/GWe or M€/GWh, but are converted post-simulation to €/kg H₂ based on hydrogen output in GWh (HHV).

5.4.1 Levelized Costs of Hydrogen

The LCOH of electrolysis reflects the total cost per unit of hydrogen produced and supplied:

$$LCOH_{Electrolyser} = \frac{Total\ Annualised\ CAPEX + Total\ fixed\ OPEX + Total\ variable\ OPEX}{Total\ Produced\ Hydrogen}$$

- **Annualised CAPEX** represents the annualised capital expenditure (M€/GWe), calculated using inputs such as total investment cost, weighted average cost of capital (WACC), economic lifetime, and corporate income tax rate. This component is further detailed in Section 5.4.2.
- **Fixed OPEX** includes annual fixed operational and maintenance costs per installed capacity (M€/GWe), and also fixed charges such as the HV grid tariff (M€/GWe), and the hydrogen backbone entry fee (M€/GW H₂).
- **Variable OPEX** covers all usage-based costs, including the variable HV grid tariff, electricity tax, and the (market) costs of feedstock electricity used by the electrolyser. These are expressed in M€/GWh_e.

The LCOH of hydrogen import reflects the total cost per unit of hydrogen imported and supplied:

$$LCOH\ Import = \frac{Total\ hydrogen\ import\ chain\ costs + Total\ fixed\ OPEX}{Total\ Imported\ Hydrogen}$$

- **Hydrogen import chain costs** represent the sum of all steps in the international hydrogen import chain [19], including: production of hydrogen in exporting country, conversion of hydrogen to ammonia, storage and handling at the export terminal, maritime transport to HIC Rotterdam, storage in Rotterdam, and cracking ammonia back to hydrogen. These costs are implemented in the model as variable OPEX per unit of imported hydrogen (with CAPEX and fixed OPEX for terminals and crackers) incorporated. This modelling approach excludes investment decisions, as it is assumed that ammonia imports can be flexibly scaled dependent on electrolysis costs and output.
- **Fixed OPEX** includes the hydrogen backbone entry fee (M€/GW H₂).

To compare both hydrogen supply routes directly, the model also calculates the cost difference between electrolysis and import:

$$LCOH\ difference = LCOH\ electrolysis - LCOH\ import$$

This value indicates the relative cost-effectiveness of domestic hydrogen production via electrolysis compared to importing hydrogen via ammonia. A negative outcome means that electrolysis is cheaper, a positive outcome means that import is cheaper.

5.4.2 Annualised CAPEX

Because the Linny-R model operates on a yearly evaluation basis, the capital expenditures (CAPEX) of all investment-based components (Electrolyser, BESS, and Salt Cavern hydrogen storage) must be converted into annual costs. This is done using a standard annualization formula, which accounts for both financing costs and linear tax treatment [84]:

$$Annualised\ CAPEX = \frac{WACC * CAPEX}{1 - (1 + WACC)^{-n}} - \frac{CAPEX * CITr}{n}$$

Where:

- CAPEX: Total Capital Expenditures (M€)
- WACC: Weighted Average Cost of Capital (%)
- n: Economic lifetime (years)
- CITr: Corporate Income Tax rate (%)

As you can see, this formula consists of two key components: base capital recovery (left part), and tax deduction effect (right part). The first part calculates the annual payment required to recover the investment, spread over the economic lifetime n , and discounted using the WACC. The WACC (Weighted Average Cost of Capital) reflects the average expected return on capital, combining the cost of debt and equity. It incorporates both market interest rates and investor risk premiums and is commonly used in techno-economic reports such as [27], [38], [85]. For immature technologies such as electrolyzers or BESS, economic lifetimes are typically short, around 15 years [27], [85], due to technological and market uncertainties. In contrast, salt cavern hydrogen storage benefits from a longer economic lifetime (30 years) due to its more technological maturity, as already proven in natural gas storage [38]. The second part represents the corporate tax benefit of depreciation, which reduces the effective annual cost of the investment. In the Netherlands, the corporate income tax rate is typically 25.8% [101], allowing part of the capital expenditure to be deducted from taxable profit over time.

5.5 Model Data

The model is based on a combination of historical data, academic sources, and technical assumptions to simulate the electricity and hydrogen system at the Port of Rotterdam region. Data was collected from publicly available datasets, scientific literature, and governmental/internal reports and studies. An overview of all parameters used in the model is provided in Appendix D. Three main categories of input data are used: static parameters, scenario-dependent parameters and dynamic parameters. Static parameters remain constant across all scenarios and model runs. Scenario-dependent parameters vary per scenario, but remain constant per model run. Dynamic parameters vary on an hourly basis throughout the simulation year. Each type of input data is further elaborated below. Two key parameters, electricity demand (a dynamic input) and hydrogen demand (a scenario-dependent input), are also briefly highlighted in dedicated subsections due to their critical role in the model.

5.5.1 Static and Scenario-Dependent Parameters

As shown in the second column of the tables in Appendix D, static parameters are fixed model inputs that remain constant in all scenarios unless explicitly varied. They show technical and economic characteristics of the electricity and hydrogen systems, such as CO₂ emission factors, technological efficiency and the value of lost load (VoLL). Most values are based on recent national studies (e.g., CE Delft, TNO, PBL); where data are missing, reasoned assumptions have been made. The third column contains scenario-dependent parameters, which are systematically varied to test the model under different conditions. These include, for example, offshore wind installed capacity, hydrogen demand, and PPA prices. Scenario values enable the model to simulate system performance under varying technological, market and policy uncertainties.

Table X-7 provides the input parameters used to calculate annualised CAPEX and fixed O&M costs for the key model components: BESS, electrolysis, and hydrogen storage in salt caverns. These are derived using standard financial assumptions; economic lifetime, WACC, and corporate income tax rate, and are converted to annual values via the annuity method (see Section 5.4.2). The resulting values are used as static and scenario-dependent cost inputs in the model.

5.5.2 Dynamic Parameters

As shown in the Graphs in Appendix D, the dynamic parameters vary on an hourly basis throughout the year, and vary per historic year. Below the dynamic parameters offshore wind capacity factor, day-ahead prices, and variable hv-grid factor are further described.

Offshore Wind Capacity Factor

Hourly offshore wind capacity factors were generated using Renewables.ninja, an open access platform developed by [87]. This platform uses historical weather reanalysis data from MERRA-2 and combines it with wind turbine power curves to estimate realistic wind energy generation profiles at specific locations. For this study, the Siemens Gamesa SG 10.0-193 DD turbine was selected, consistent with the turbine model used in recent Dutch wind farms such as Hollandse Kust Noord and Zuid [102]. Its specifications are: 10 MWe rated power, a 193 meter rotor diameter, and a 140 meter hub height. The wind profile was based on the average coordinates of the six different wind farm sites in the IJmuiden Ver wind area (52.7988° N, 3.4513° E), as defined by RVO [103]. To generate a normalized hourly capacity factor (0-1), the installed capacity in Renewables.ninja was set to 1 kW.

Year Selection and Day-Ahead Price

The base simulation year used in the model is 2024. Hourly day-ahead (DA) electricity prices for 2024, along with those for 2022, were retrieved from [88], ensuring a consistent and reliable data source across all simulation years.

2024 was selected as the base year for several reasons. Firstly, 2024 is the most recent year with complete hourly meteorological and price data available at the time of this study. Secondly, according to The Oxford Institute For Energy Studies [104], 2024 included two significant Dunkelflaute events (periods of low wind and solar generation), particularly in January and November. This enables robust testing of system flexibility under stress conditions, such as a low wind

profile in combination with high DA prices and a high electricity demand. Lastly, 2024 reflects a partial return to normal market conditions after the extreme volatility of the energy crisis in 2021–2022, but yet it still shows persistent variability in price signals, making it useful for analysing flexibility.

To test the sensitivity of the model to weather variability and price, an additional years, 2022, was simulated. This year was characterised by exceptionally high and volatile electricity prices due to the European energy crisis. This year is included to analyse the impact of extreme price spikes on system behaviour of the model.

These years have been chosen to reflect a range of possible market futures. Price volatility is expected to increase in the short term due to the rising share of renewables and the closure of fossil flexible generation capacity. In the long term, it may decrease as storage and flexible demand options mature [26]. This multi-year approach provides valuable insight into the robustness of the system under different future scenarios.

Variable HV Grid Factor

As of 2025, Dutch HV grid tariffs consist of both a fixed and a variable component [100], [105]. To integrate both tariff components into the model, the fixed component has been included as a static, scenario-dependent variable. This fixed cost is expressed as a yearly amount, determined by the required maximum electrical capacity (GWe) per year.

The variable component is typically calculated based on the monthly maximum electrical capacity (in kW), weighted using a factor ranging from 0 to 1. This factor varies depending on the time of day, weekday versus weekend, holiday status, and month of the year. Figure 5-10 below illustrates the implemented hourly distribution of the HV grid factor across a representative year.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.8
Feb	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.8
Mar	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	0.9	0.8	0.8
April	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
May	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
June	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
July	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Aug	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Sep	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Oct	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	0.9	0.8	0.8
Nov	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0	0.9	0.8	0.8
Dec	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.8
weekend/holiday	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Figure 5-10: Variable HV Grid Factor (Adapted from [100], [105])

To incorporate this into the model in an hourly format, the EHS (Electricity High-Voltage System) tariff of €7.14 per month was used [100]. This amount was annualized (multiplied by 12) and scaled by a factor of 0.76 (average variable HV grid factor), divided over 4800 full-load hours. This conversion results in an hourly-distributed variable HV grid tariff. The final hourly cost is calculated by multiplying the base hourly tariff by the time-dependent variable HV grid factor, thereby capturing the variation in cost throughout the year. While this variable HV grid fee applies to all electricity consumers, in the model it is only varied in the scenarios for the electrolyser. This isolates its impact, allowing for a clearer analysis of its specific effect on LCOH of Electrolysis.

Electricity Demand

Electricity demand projections for HIC Rotterdam and the hinterland are based on both internal and public sources, including [21], [43], [56], [86], [94], [106] as well as [11], [46], [107]. These sources consistently project a steep rise in industrial electricity demand over the coming decades. Figure 5-11 below shows annual electricity consumption scenarios (including Electrolysis) for the Rotterdam–Moerdijk region in TWh, including various storyline trajectories (e.g., national, European, international) and the network operators’ base case [46].

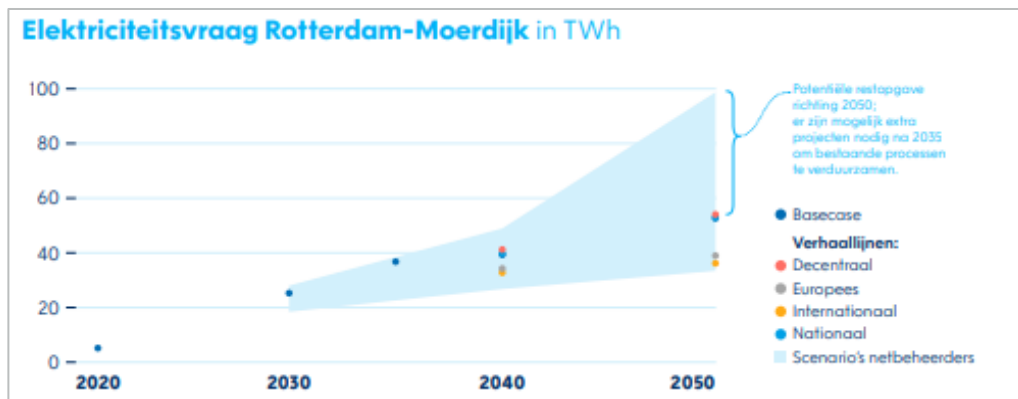


Figure 5-11: Projected electricity demand in the Rotterdam–Moerdijk region [11]

DNV (2025) [56] has estimated that industrial electricity usage at HIC operates at ~7300 full load hours per year. To reflect typical daily load profiles, it is assumed that electricity demand is equal to 70% of peak load between 21:00–07:00 and on weekends. Based on internal and public data, the following annual demand and peak load scenario estimates are concluded for HIC Rotterdam (without electricity consumption by electrolysis):

- Low: 15 TWh/year - Peak load: ~2 GW
- Mid: 30 TWh/year - Peak load: ~4 GW
- Peak: 45 TWh/year - Peak load: ~6 GW

The electricity demand of the hinterland, is estimated a factor (Low: 0.1375; High: 0.275) of total Dutch system load, based on modelling assumptions in [86] and national demand data from ENTSO-E [88]. The scenarios values of the dynamic parameters, electricity demand of HIC and hinterland, are shown visually in Appendix C.0.

Hydrogen Demand

Hydrogen demand projections for HIC Rotterdam and the hinterland are also based on both internal and public sources [11], [94]. These sources reflect the expected increasing role of hydrogen as a feedstock and energy carrier in industrial decarbonisation, especially for refining, ammonia, and high-temperature processes. Figure 5-12 below presents the expected hydrogen demand scenarios for the Rotterdam–Moerdijk region, showing a consistent upward trend towards 2050 across various national and international policy pathways.

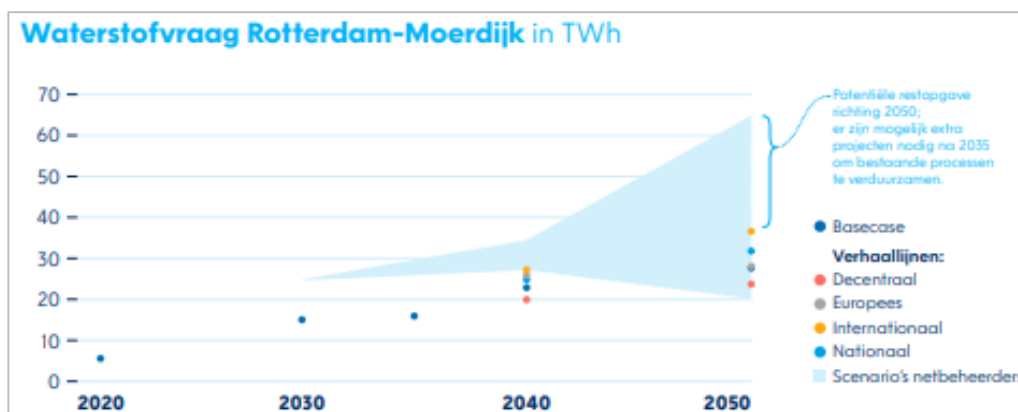


Figure 5-12: Projected hydrogen demand in the Rotterdam–Moerdijk region [11]

Based on the reported uncertain trajectories, the following annual demand and corresponding baseload peak values are used for modelling hydrogen demand at HIC Rotterdam:

- Low: 15 TWh/year – Equivalent to 1.7 GW continuous demand
- Mid Low: 30 TWh/year – Equivalent to 3.4 GW continuous demand
- Mid High: 45 TWh/year – Equivalent to 5.1 GW continuous demand
- Peak: 60 TWh/year – Equivalent to 6.8 GW continuous demand

The hourly values on the right are converted from the annual values on the left and assume a flat hourly baseload profile over the whole year (8760 hours), reflecting the continuous nature of industrial hydrogen consumption. This baseload assumption simplifies demand- side modelling and reflects the steady operational needs of hydrogen end-users.

In this study, only the Connected Deep Green (CDG) scenario is used to estimate hydrogen demand for the hinterland. Among the four future scenarios developed by the Port of Rotterdam [11], [94], CDG most closely reflects current Dutch and EU policy ambitions, including the 4 GW hydrogen production target for 2030 and the goals of REPowerEU. It assumes strong international cooperation, rapid decarbonisation, and large-scale (green) hydrogen deployment. To represent hinterland demand, HIC Rotterdam demand is scaled by a fixed factor of 1.1053, as defined by the CDG scenario. This scaling is applied consistently across all HIC Rotterdam hydrogen demand levels.

5.6 Model Verification

This section assesses whether the conceptual and specified model has been correctly implemented in Linny-R. This is done by verification, which is conducted by examining how key components of the system behave under expected and varied input conditions [108]. This helps ensure that the model produces logical, explainable results and is robust enough for the next phase of the modelling cycle: experimentation. The verification is primarily conducted over the month March in base year 2024 ($t = 1416$ -2160 h), allowing for a more detailed analysis at hourly resolution than full-year simulations. An exception is made for the Dunkelflaute analysis, which is assessed over the period October to December 2024.

5.6.1 Supply and Demand

The first graph shows the total electricity demand (red line) against supplied electricity from offshore wind (orange), grid electricity (green), BESS discharges (blue), and load shedding (purple) in the base case. The model behaves logically: wind electricity curtailment (grey) generally occurs when supply exceeds demand, and spikes in grid electricity usage are seen during low wind periods. In general, high DA prices are accompanied by demand fall, while low DA prices are accompanied by demand increase. It is notable that negative DA prices result in curtailed wind, while grid electricity captures this difference. This can be explained by the fact that wind electricity is being prioritized over grid electricity due to its very small actor weight advantage (0.00005 vs 0), as explained earlier in Section 5.2.1. This results in no ‘system loss’ when grid electricity is sold with negative DA prices, in contrast to a very small ‘system loss’ when wind electricity is sold at negative prices.

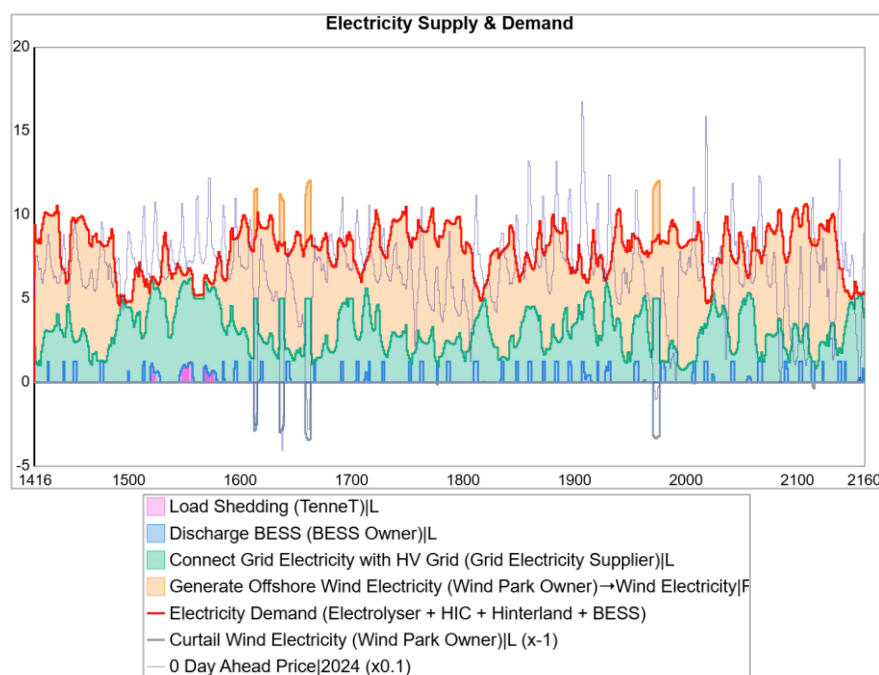


Figure 5-13: Verification - Electricity Supply & Demand (base case)

This scenario (second graph) shows the flat hydrogen demand (red line) met by green hydrogen from electrolysis (blue area) and ammonia imports (orange area), in the base case. As can be seen, no hydrogen storage is active. The system prioritises electrolysis when wind electricity is available, with imports covering residual demand. In this way, the model can estimate the need for hydrogen imports in addition to production from electrolysis. Moreover, it allows cost-effective comparison of hydrogen from electrolysis and imports.

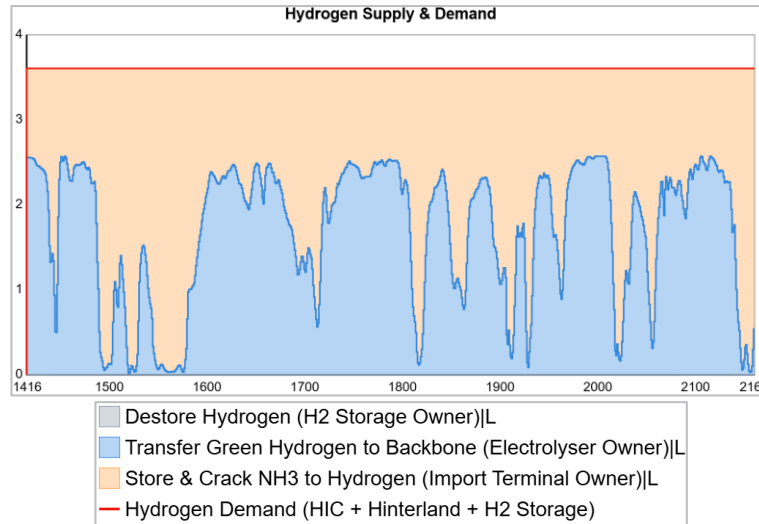


Figure 5-14: Verification - Hydrogen Supply & Demand (base case)

To demonstrate the models' operation of hydrogen storage, demand shedding, and withdrawn hydrogen, the base case was modified by replacing the optimised, scalable store and crack NH₃ capacity with fixed values: 3 GW (left figure) and 2 GW (right figure).

In the left figure, total hydrogen demand (red line) is no longer flat due to the active role of hydrogen storage. Demand is met by a combination of green hydrogen from electrolysis (blue), hydrogen imports (orange) and hydrogen from storage discharge (grey). The black line represents withdrawn hydrogen (oversupply), which occurs when production exceeds demand and storage capacity. This confirms that storage is only charged for when surplus hydrogen is available, in line with expected model logic.

In the figure on the right, the lower hydrogen import capacity leads to a period (t = 1500-1600 h) in which the demand for hydrogen cannot be fully met due to low wind speeds, resulting in little wind electricity being available for the electrolysis plant. As a result, the model activates demand shedding (purple) to balance the system. Storage continues to operate realistically, discharging only when demand exceeds production and imports, and remains inactive during periods of shortage. This behaviour confirms the correct implementation of both storage and shortage processing mechanisms.

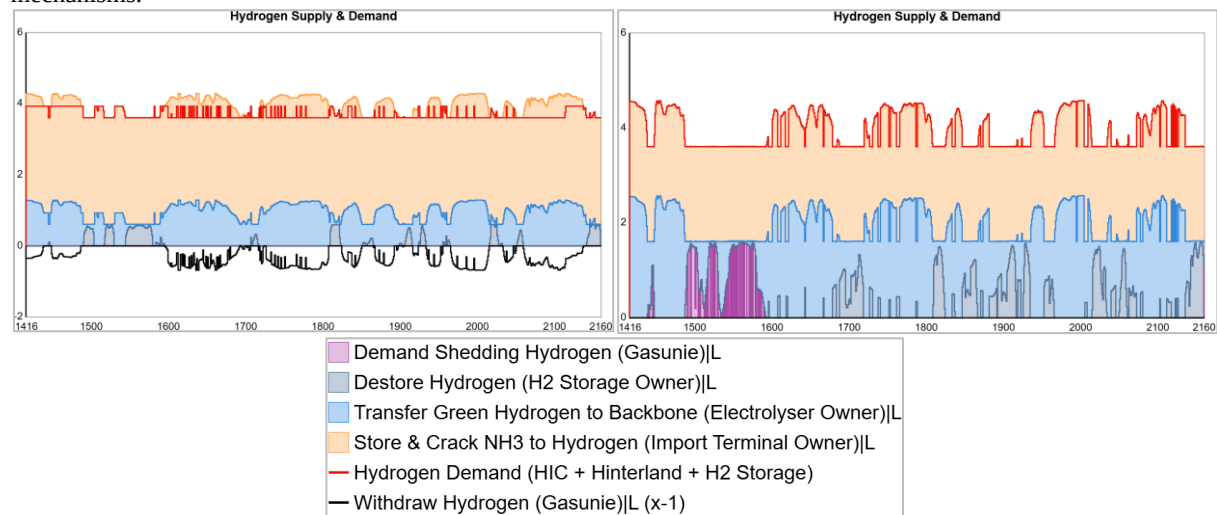


Figure 5-15: Verification - Hydrogen Supply & Demand (fixed import capacity cases)

5.6.2 Electricity Market

The graph below shows total electricity demand (red line) alongside electricity sold via the market from different sources: wind (split into PPA and DA), grid, and BESS. The results are consistent with Figure 5-13, now with wind electricity disaggregated. The figure confirms that the electricity market is balanced, and wind electricity is evenly split between PPA and DA sales, as assumed in the base case.

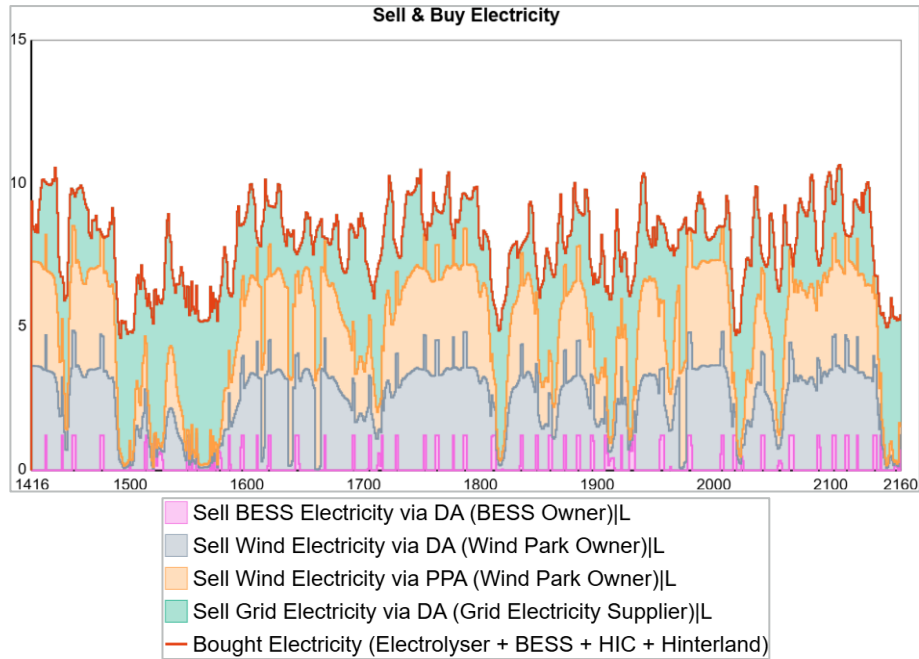


Figure 5-16: Verification - Electricity Market (base case)

The graph below illustrates the case of full PPA commitment (in December), meaning that all wind electricity is allocated to the electrolyser, which is allowed to resell this on the DA market. The figure shows that electricity is mainly resold when generation exceeds the optimal installed capacity of the electrolyser (about 6 GW). Moreover, it can be observed that the DA price spikes (red line) influence resale decisions, especially during periods of lower wind generation. This suggests that in the current model set-up, resales are driven by both capacity constraints and by DA price signals. This is in line with expectations, as electrolyzers are capital-intensive assets and benefit from high Full Load Hours, giving self-consumption priority over resale unless DA prices are very high. This result is understandable as the model is configured to minimise total system costs rather than maximise electrolyser profits. While this limits the role of market-based arbitrage, it provides a useful system-level benchmark for cost-optimal operation. This trade-off, in context of individual actor incentives versus system-wide optimisation, could be discussed further in future research.

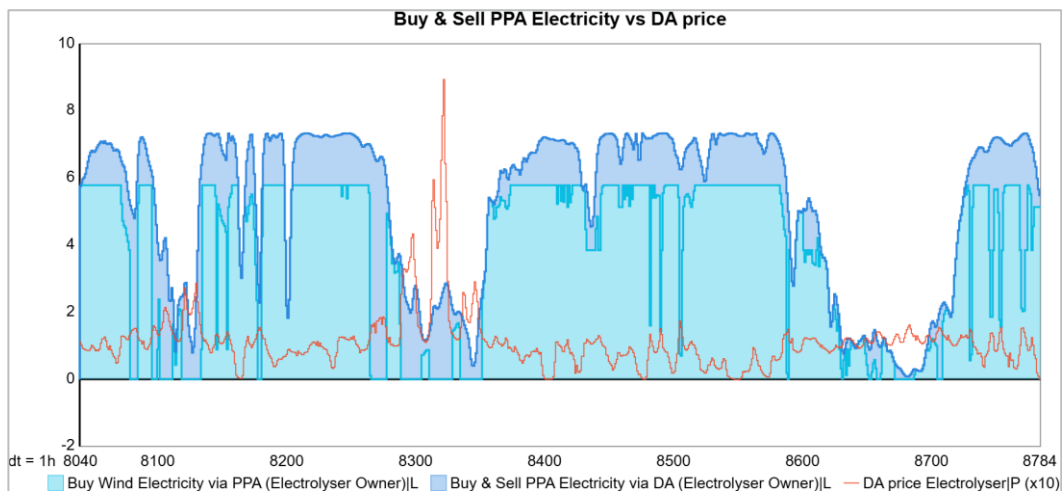


Figure 5-17: Verification - Buy & Sell PPA Electricity (full PPA requirement case)

5.6.3 Influence of Variable HV Grid Fee

To analyse the impact of dynamic parameters—specifically the HV variable grid fee factor (Section Variable HV Grid Factor), the graphs below show the optimised behaviour of BESS (Figure 5-18) and Electrolysis (Figure 5-19) in a free market scenario. In this case, the base model is adjusted to allow the electrolyser to choose between buying electricity via PPA or on the DA market. DA prices are also included in the analysis to capture their potential influence.

In Figure 40, the variable grid fee factor (red) clearly affects BESS charging behaviour (yellow). The model charges the BESS predominantly during hours with low grid fee factors, avoiding grid use when tariffs are high, consistent with the policy objective behind time-differentiated tariffs [100] to reduce grid congestion. This effect is particularly explainable due to the high flexibility of the BESS, which does not depend on a fixed electricity demand profile. While BESS charging primarily responds to low variable grid fee factors, the DA price (black) has some influence. As can be seen, it still tends to buy during price dips, which aligns with the models' cost-minimisation logic.

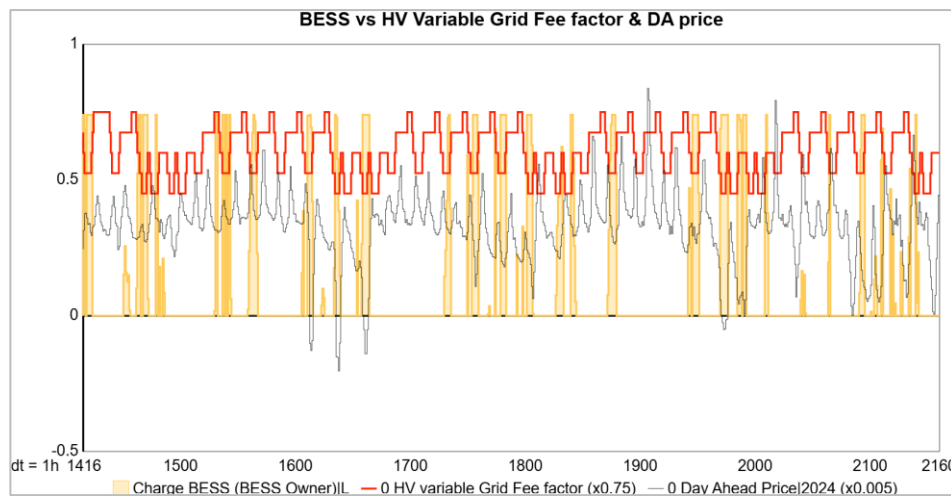


Figure 5-18: Verification - BESS vs HV Variable Grid Fee factor & DA price (free DA/PPA choice case)

In Figure 5-19, the influence of the variable grid tariff factor (red) on electrolyser electricity procurement (purple) is much smaller. This means that even in a free market situation, where PPA vs DA procurement is unrestricted, electrolyser's electricity demand is largely determined by available offshore wind capacity (yellow) rather than by tariff fluctuations (red) or electricity prices (black). This indicates that electricity procurement for electrolysis remains mainly supply-driven and is limited by wind availability, rather than being actively optimised based on grid tariffs or market price signals.

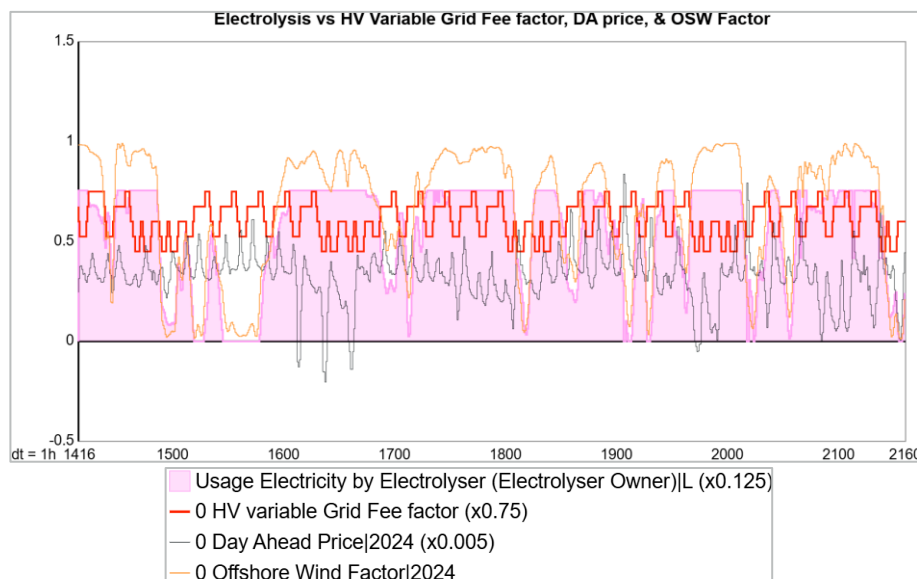


Figure 5-19: Verification - Electrolysis vs HV Variable Grid Fee factor, DA price, & OSW Factor (free DA/PPA choice case)

5.6.4 Dunkelflaute

According to the Oxford Institute For Energy Studies [104], Dunkelflaute events, periods of very low wind and solar generation, occurred in base case year 2024 in January and November. To test the model's performance under these conditions, the base input case was simulated for the months of October, November, and December.

As can be seen in the graph below, the results confirm expected behaviour: when the offshore wind capacity factor drops to zero, the system experiences shortages that trigger load shedding. These shortages are penalised at VoLL, indicating unmet demand. This response confirms that the model correctly reflects system stress during Dunkelflaute events and applies economic penalties for supply inadequacy in line with the modelling assumptions.

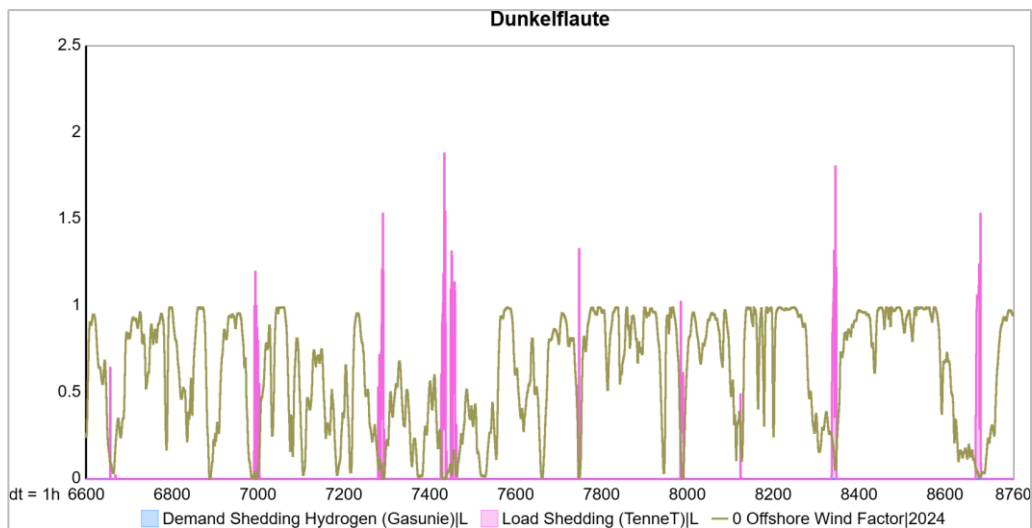


Figure 5-20: Verification - Dunkelflaute (base case)

5.6.5 Storage Behaviour

Figure 5-21 shows the behaviour of the BESS during the first two weeks of March 2024 in the base case. The battery behaves as expected: charging (blue) and discharging (green) never take place simultaneously and the state of charge (orange) follows a regular cyclic pattern. The BESS undergoes several full cycles (a fully filled + emptied storage) in a short time, in line with its intended role as a short-cycle storage solution on hour-scale operation. At time step 1550, a shortage (black) occurs while the battery still contains electricity. This minor, unrealistic artefact results from the solver's perfect foresight: knowing future supply and demand, it retains electricity to cover a larger shortage later, prioritising total optimisation over short-term needs. The storage is empty both at the beginning and at the end of the simulation, which is also due to the full prior knowledge of the model. To ensure fair optimisation, all simulations start with an empty BESS.

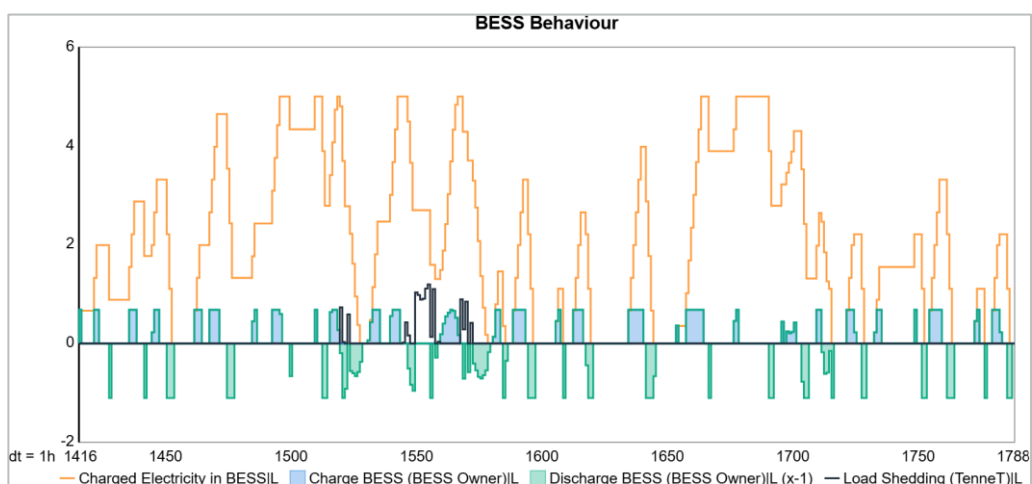


Figure 5-21: Verification - BESS Behaviour (base case)

Figure 44 presents the hydrogen storage (salt cavern) behaviour under a fixed import capacity (2 GW) scenario. The system also avoids simultaneous storing (pink) and destoring (light blue), and the state storage (orange) shows a few cycles, fewer than the BESS, which aligns with its role as a medium-cycle storage (multi-day to biweekly). During some timesteps period, hydrogen demand shedding (dark blue) occurs while storage still holds hydrogen. This is explained by limited hourly withdrawal capacity: the cavern cannot discharge quickly enough to meet sudden peaks, which is realistic.

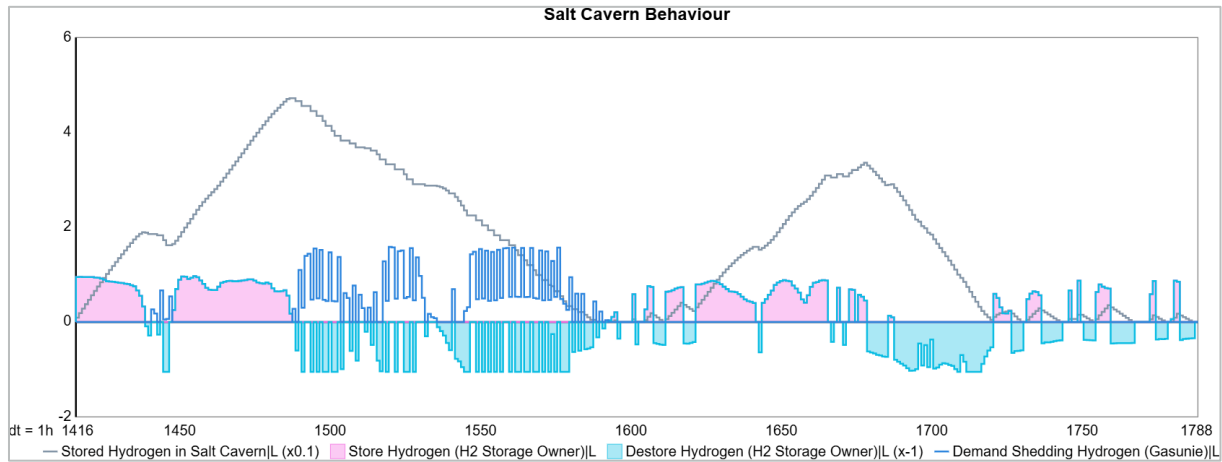


Figure 5-22: Verification - Salt Cavern Behaviour (fixed import capacity case)

5.7 Main Takeaways on Implementation

This chapter has implemented the conceptual model into a fully functional simulation in Linny-R. All key system components—offshore wind, grid electricity, electrolysis, ammonia imports, storage, and demand—were translated into model clusters with hourly resolution. The model applies cost-based optimisation and includes key technical and economic parameters, allowing comparison between domestic hydrogen production and imports. Verification confirmed that the model behaves as expected under typical and stress conditions, ensuring it is ready for the experimentation phase in the next chapter.

6 Experimentation

This chapter presents the experimentation phase of the modelling & simulation life-cycle. Experiments were conducted to assess the effect of key uncertainties within the XLRM framework on the defined KPIs. The aim is to generate insights that support the answering of the research questions. The chapter begins with a description of the experiment design and parameters, followed by a sensitivity analysis (Experiment 1), a series of scenario-based experiments (Experiments 2–5), and an analysis of the results. Finally, the results are discussed and validated in the context of existing literature.

6.1 Experiment Design and Parameters

As introduced in Section 3.1.2, this experimentation phase follows the Exploratory Modelling and Analysis (EMA) approach, which systematically explores the effects of external (X) and policy-levers (L) on system relationships (R) and performance metrics (M) within the defined XLRM framework. This method enables the identification of robust insights across a broad range of plausible futures, thereby supporting the answering of the research questions.

A total of five experiment series were developed. The first is a sensitivity analysis, varying all parameters individually (+/-20%). The remaining four are scenario-based experiments involving specific parameter combinations. Each unique combination of input parameters defines a scenario, which is simulated using Linny-R. These experiment collectively cover over 400 distinct scenarios, each reflecting a different potential system configuration. The parameters used in these experiments are categorized into two types: general and experiment-specific. General parameters are varied across multiple experiments, while experiment-specific parameters are tailored to one particular experiment. This setup enables a structured evaluation of how each parameter influences the KPIs.

The experiments are designed to align with sub-question 1 and 2 of this study and follow a logical sequence. The sensitivity analysis in Experiment 1 provides the foundation by identifying key influential parameters. The following scenario-based experiments (2-5) build on these insights, each focusing on specific dynamics such as cost competitiveness, operational flexibility or strategic interventions. The design of Experiments 2–5 allows for cross-experiment analysis (Section 6.2.6), enabling comparison across uncertainty ranges to identify robust patterns and system vulnerabilities—in line with EMA principles.

Table 6-1 summarises the objective, scope, targeted SQ, and number of scenarios per experiment.

Table 6-1: Overview of Experiment Design

Experiment	Name	Objective	Varied Parameters	Targeted SQ	Scenarios
1	Base Case & Sensitivity	Establish base case and identify most influential parameters	All experiment parameters (-20%, base, +20%)	SQ 1	49
2	Multi-Sensitivity LCOH	Identify breakeven conditions for domestic hydrogen vs. imports	CAPEX, import price, and PPA price	SQ 1	75
3	System Flexibility & Resilience	Assess system flexibility and performance under demand and supply variation	Grid/wind supply, electricity/H2 demand, and electricity storage	SQ 2	200
4	Fixed H2 Import	Tests competitiveness when import capacity is fixed (pushes domestic role)	Fixed H2 import capacity, and wind supply	SQ 2	27
5	Extreme H2 Supply	Evaluate system response under extreme supply constraints & assess influence of electrolysis grid access	Wind supply, PPA requirement, grid access electrolyser, and low/high H2 demand	SQ 2	96

Before presenting the experiments, Table 6-2 below provides a structured overview of the parameters varied across these scenario-based experiments. It specifies whether each parameter can be considered as an external factor or a policy lever within the system, lists the corresponding scenario values, and indicates the experiments in which each parameter is applied. Bolded values indicate the base case values used in Experiment 1, with additional bolded values included in Appendix D.1, along additional details (e.g., assumptions, sources).

Table 6-2: Overview of Experiment Parameters (Experiments 2-5)

Parameter	External factor (X) / Policy lever (L)	Scenario Values	Varied Across Experiment
Electricity System			
Max. Installed Grid Supply Capacity (GWe)	X	4, 4.5, 5, 5.5, 6	3
OSW Installed Capacity (GWe)	L	7.4, 13.4, 19.4	3, 4 (fixed at Mid), 5
Max. Installed Storage Capacity BESS (GWhe)	L	5, 20, 35, 50	3, 4/5 (fixed at 50)
Max. Charge/Discharge Capacity BESS (GWe)	L	1.25, 5, 8.75, 12.5	3, 4/5 (fixed at 12.5)
Electricity Demand – HIC Rotterdam (GWhe/hour)	X	Low; Mid; Peak	3/4/5 (fixed at Mid)
Electricity Demand – Hinterland (GWhe/hour)	X	Low; Peak	3, 4/5 (fixed at Peak)
PPA price (€/MWhe)	L	40; 80 ; 120	2
PPA requirement (% of OSW)	L	0; 50	4 (fixed at optional), 5
Hydrogen System			
Max. Installed Capacity NH ₃ Cracker (GW H ₂)	L	0, 1, 2, 3, 4, 5, 6, 7, 8, Unlimited	4, 5
HV Grid Access Electrolyser (% of OSW Installed Capacity)	L	0 , 50	5
H ₂ Demand - HIC Rotterdam (TWh H ₂ /year)	X	15, 30, 45, 60	3, 4 (fixed at Mid Low), 5
Annualised CAPEX + O&M Electrolysis (M€/GWhe/year)	L	25%; 50%; 75%; 100% (433)	2
H ₂ Import Price (€/kg H ₂)	X	50%; 75%; 100% (7.70) ; 125%; 150%	2

6.2 Model Results

This section presents the results of the experiments conducted, structured according to the objectives defined in the experiment design. Each experiment begins with a brief description of the purpose of the experiment, outlining the goal within the broader research context, and includes a small hypothesis that is proposed at the outset. This hypothesis is designed to guide the experiment and establish expectations for the outcomes. For each experiment, both logical and illogical results are described and interpreted in relation to the underlying assumptions, focusing on the main causes and limitations observed. This structured approach ensures that the results contribute directly to answering the sub-questions of this study. In addition to the individual experiment results, a cross-experiment analysis is included. This analysis compares outcomes across scenario-based experiments (2–5) to identify robust patterns and system sensitivities within the broader uncertainty space. The complete set of experiment results is provided in Appendix E.1; in this section, only the most important results per scenario are presented.

6.2.1 Experiment 1: Base Case & Sensitivity

This experiment establishes a base scenario and explores the individual sensitivity of input parameters through a +/-20% variation. The objective is to determine which techno-economic factors significantly affect the KPIs. This experiment supports the identification of critical levers (SQ1) for domestic hydrogen competitiveness.

The results of Experiment 1 are categorised according to the four A's framework, with each category further broken down into the KPIs defined in Section 4.2.1. The sensitivity results below are visualised using tornado charts, with a full sensitivity heatmap available in Appendix E.1. Operational sensitivities—such as installed capacities, full load hours, and storage cycle rates for Electrolysis, NH₃ Cracking, BESS, and Salt Cavern storage—are also included in Appendix E.1 but are not further discussed here.

Availability

Figures 6-1 and 6-2 below show the top 6 sensitivities of Expected Energy Not Delivered (EENS) and Loss of Load Expectation (LOLE) to input variations.

As hypothesis, it is expected that system availability in the base case is most sensitive to parameters that directly constrain electricity supply capacity, such as maximum grid supply and offshore wind capacity, while hydrogen-related parameters have a negligible effect due to the assumed optimised unlimited import capacity. Electricity storage capacity is expected to play a secondary but notable role by mitigating short-term imbalances.

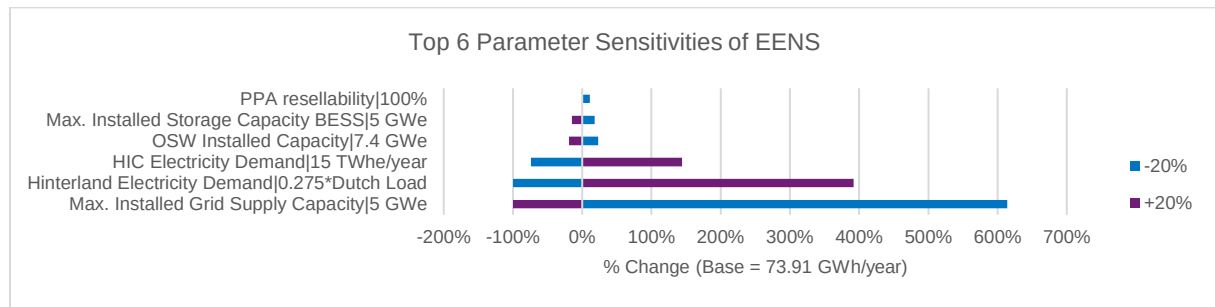


Figure 6-1: Experiment 1 - Sensitivity of Expected Energy Not Served (EENS) to Top 6 Parameters

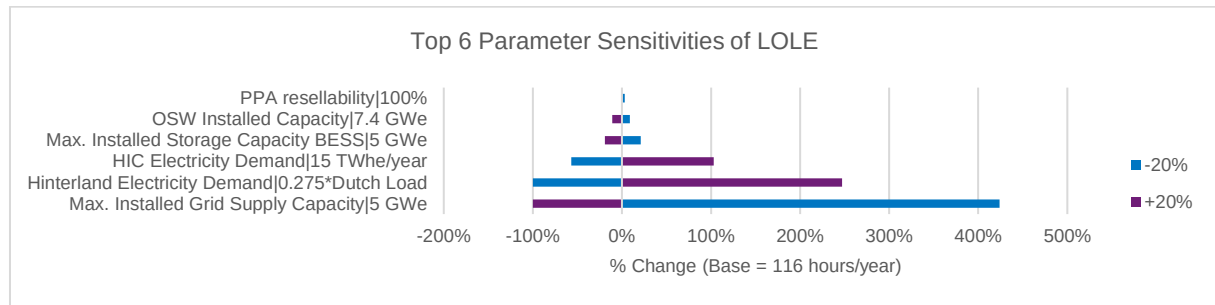


Figure 6-2: Experiment 1 - Sensitivity of Loss of Load Expectation (LOLE) to Top 6 Parameters

As can be seen in the figures above, the results confirm that system availability in the base case is primarily driven by electricity demand and supply constraints:

- Maximum installed grid supply capacity is the most influential factor: a 20% reduction increases EENS by +614% and LOLE by +424%, while a 20% increase completely eliminates shortages. This confirms the expectation of extreme system sensitivity to this parameter. Therefore, this parameter is further investigated in Experiment 3.
- Electricity demand significantly impacts system availability, whereas hydrogen demand has negligible influence, as expected, due to unlimited imports in the base case.
- OSW capacity affects EENS (-19%, +23%) more than LOLE (-11%, +9%), aligning with the expectation that it reduces shortage severity but cannot prevent shortage hours during low wind periods.
- BESS capacity adjustments of $\pm 20\%$ lead to roughly $\pm 20\%$ changes in both EENS and LOLE, supporting the expectation that storage plays a secondary but important role. Given the relatively small base case capacity (5 GWe), even modest changes have a substantial effect; hence, BESS is further examined in Experiment 3.
- The decrease in PPA resellability mainly affects EENS (+11%) over LOLE (+3%), indicating a notable role for electrolyzers in reselling PPA electricity and thereby reducing energy shortages.
- Price-related factors (e.g. PPA price) have minimal impact on system availability, emphasizing the model's focus on physical constraints rather than market mechanisms as its primary drivers.

Accessibility

Figure 6-3 below presents the top 8 sensitivities of the Domestic Electrolyser H2 Share (H2-E Share) to input variations. As hypothesis, it is expected that the electrolyser share to be driven primarily by hydrogen demand, with OSW capacity and PPA requirements acting as key secondary factors by determining the wind electricity availability for electrolyzers. Electricity and hydrogen prices are expected to have a moderate effect, with lower electricity prices boosting the electrolyser share, while lower shipped ammonia prices may reduce it.

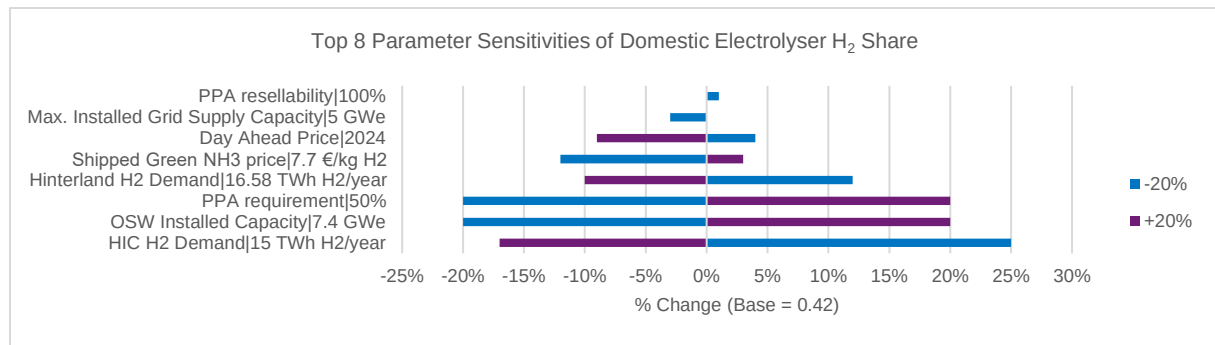


Figure 6-3: Experiment 1 - Sensitivity of Domestic Electrolyser H₂ Share (H₂-E Share) to Top 6 Parameters

The figure above confirm that system accessibility to hydrogen from electrolysis in the base case is mainly driven by hydrogen demand, wind electricity availability, and energy prices:

- Hydrogen demand (HIC + Hinterland) has the largest impact, in line with expectations. Since hinterland demand is modelled as a factor of HIC demand (see Section 5.2.7), increases in HIC demand effectively scale both, explaining its stronger influence on H₂-E Share.
- OSW installed capacity and the PPA requirement show symmetric $\pm 20\%$ effects on electrolyser share, confirming the anticipated direct link between wind electricity availability, allocation rules, and electrolysis operation.
- A reduction in maximum installed grid supply capacity slightly decreases H₂-E Share (-3%), consistent with expectations as more wind electricity is diverted to meet non-electrolysis demand.
- Shipped green ammonia price (-10%, +12%) and day-ahead electricity price (+9%, -4%) have notable but smaller impacts. The strong effect of price decreases supports confirms that lower electricity prices promote, while lower ammonia prices discourage, higher electrolyser share. This highlights the role of both electricity and hydrogen import prices in domestic hydrogen production.

Acceptability

Figure 6-4 below presents the top 8 sensitivities of Average CO₂ Emission (Avg. CO₂) to input variations.

As hypothesis, it is expected that average CO₂ intensity in the base case is driven primarily by emission factors, in particular the grid electricity emission factor, with other parameters playing only a minor role.

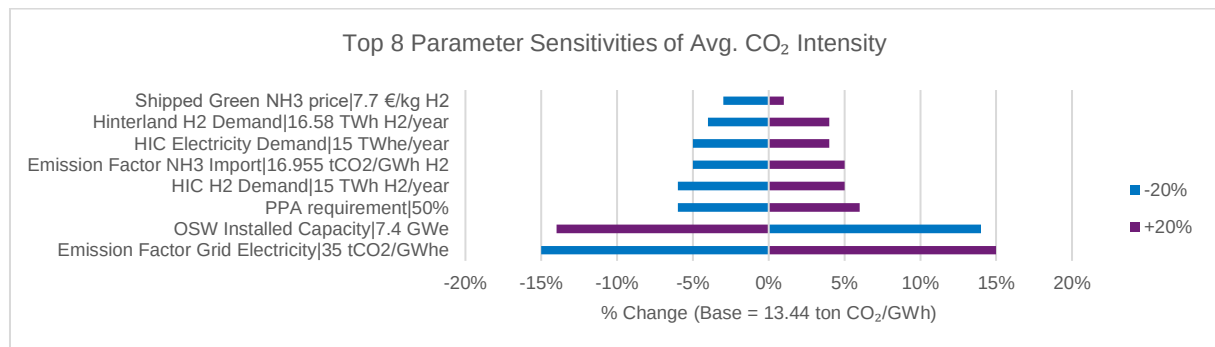


Figure 6-4: Experiment 1 - Sensitivity of Average CO₂ Emission (Avg. CO₂) to Top 8 Parameters

The figure above confirms that average CO₂ intensity in the base case is primarily driven by electricity emissions, while also highlighting the influence of wind electricity availability, demand levels, and a smaller role for import emissions:

- Grid electricity emission factor and OSW installed capacity have the strongest impact ($\pm 15\%$), confirming the key role of emission factors and thereby wind electricity availability in reducing CO₂ intensity.
- PPA requirements also reduce CO₂ intensity by increasing the share of domestic hydrogen instead of imported hydrogen, representing a stronger effect than initially expected.
- Hydrogen demand (HIC + Hinterland) and NH₃ import emissions have moderate effects, reflecting their influence on the electricity mix and import-related emissions.

- Cost related factors (e.g., PPA price) have minimal impact, in line with the expectation that price shifts do not meaningfully affect CO₂ intensity in this model.

Affordability

Figures 6.5–6.8 below show top sensitivities of LCOH_{electrolysis}, LCOH_{import}, LCOH Difference, and Average System Costs (Avg. SC) to input variations.

As hypothesis, it is expected that affordability in the base case is primarily determined by structural cost drivers—particularly electricity prices, electrolyser CAPEX & O&M, and import prices—while grid capacity and demand mainly influence overall system costs through shortage-related penalties. Storage capacity is expected to have a secondary but notable role in cost reduction by mitigating shortages.

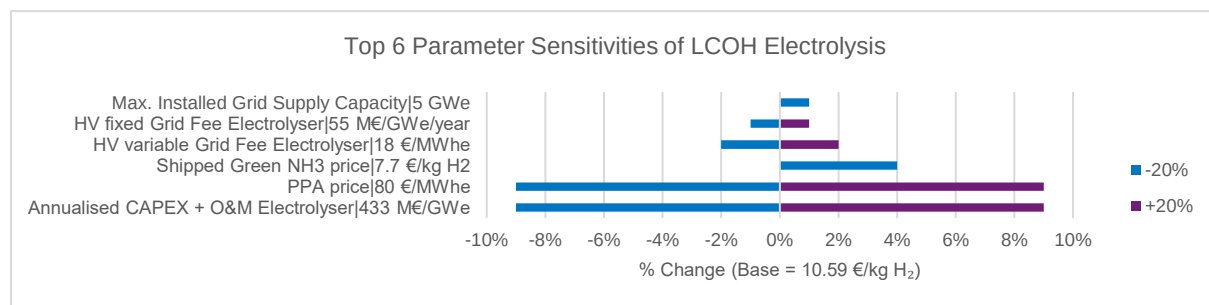


Figure 6-5: Experiment 1 - Sensitivity of Levelized Costs of Hydrogen by Electrolysis (LCOH_{electrolysis}) to Top 6 Parameters

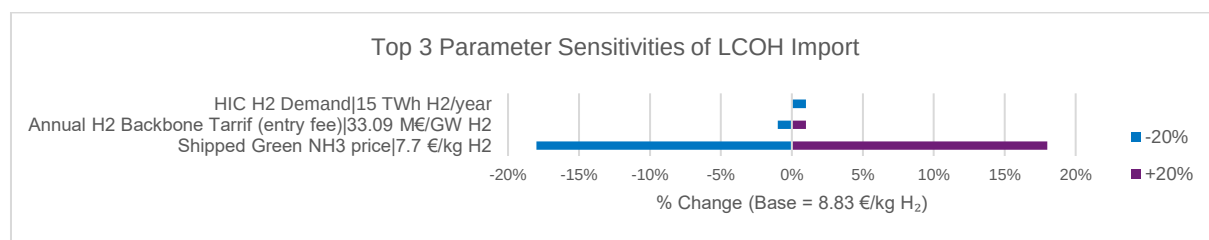


Figure 6-6: Experiment 1 - Sensitivity of Levelized Costs of Hydrogen from Imports (LCOH_{import}) to Top 3 Parameters

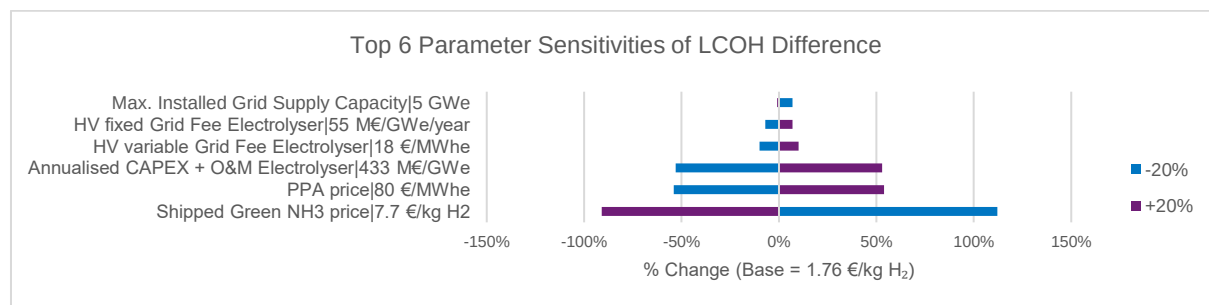


Figure 6-7: Experiment 1 - Sensitivity of Levelized Costs of Hydrogen Difference (LCOH Difference) to Top 6 Parameters

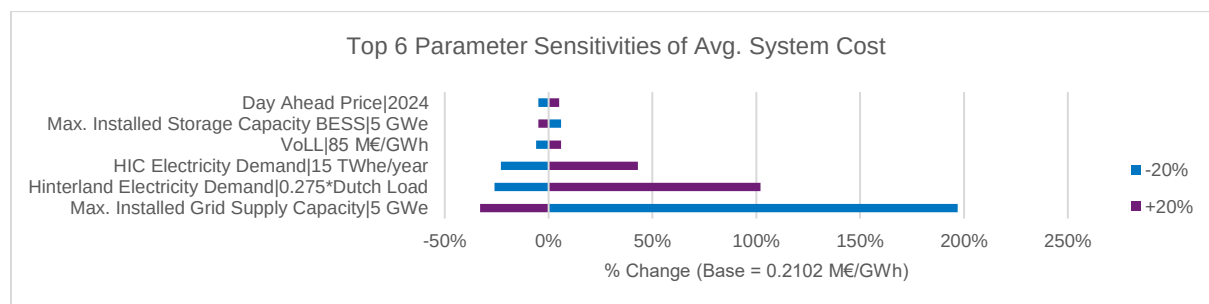


Figure 6-8: Experiment 1 - Sensitivity of Average System Costs (Avg. SC) to Top 6 Parameters

Figure 6-5 shows that LCOH_{electrolysis} in the base case is mainly driven by electricity costs and CAPEX + O&M:

- PPA price and electrolyser CAPEX & O&M have the largest impact ($\pm 9\%$), confirming their dominant role in domestic hydrogen production costs (aligned with TNO [27]).
- Shipped green NH_3 price has a moderate effect, but only through price decrease (+4%), which was not expected. This is explained by lower NH_3 prices shifting demand toward imports, reducing electrolyser utilisation and increasing cost per kg, while higher prices have no effect because domestic production is already maximised due to the PPA.
- HV grid fees only have a minor effect ($-/+2\%$ for variable fees, $-/+1\%$ for fixed fees), despite being frequently mentioned as potential source of cost reduction (see Section Cost Drivers). Given their limited influence in this model, grid fees are not included in the main experimental design, but are addressed separately in Appendix E.6.
- Grid supply capacity has minimal influence, in line with expectations, with small increases in cost only during low-wind periods, forcing sales of PPA electricity to fulfil the systems' electricity demand.

Figure 6-6 shows that $\text{LCOH}_{\text{import}}$ in the base case are almost entirely determined by the shipped NH_3 price ($\pm 18\%$), as expected. This negligible impact of hydrogen backbone tariffs and demand, indicate that $\text{LCOH}_{\text{import}}$ in the model is largely self-contained and depends on the pricing of external supply.

Figure 6-7 highlights that LCOH Difference (electrolysis vs. import) in the base case is logically dominated by NH_3 price, PPA price, and electrolyser CAPEX & O&M. These three factors are the key drivers of the cost gap between domestic production and imports, which is why they are further investigated in Experiment 2.

In contrast, installed grid supply capacity and grid fees have a smaller, secondary impact on LCOH Difference. However, since grid supply capacity significantly influences several other KPIs, it is further examined in Experiment 3.

Figure 6-8 shows that average system costs in the base case are primarily driven by electricity system parameters:

- Grid supply capacity and electricity demand emerge as the dominant drivers of average system costs, consistent with the hypothesis that shortages—priced via VoLL—are the main mechanism linking these factors to affordability (see Appendix E.1).
- Grid supply capacity is particularly dominant, with a 20% decrease increasing Avg. SC by +197%, while a 20% increase reduces it by -33%.
- Electricity demand (HIC + Hinterland) also shows strong sensitivity, with reductions lowering costs ($\sim -25\%$) and increases raising costs by +40% to +100%.
- BESS capacity shows a secondary but notable effect ($\pm 5\%$), supporting the hypothesis that storage plays a cost-reducing role by limiting shortages; hence, it is examined in more depth in Experiment 3.

Overall, the affordability analysis shows that hydrogen production costs are primarily driven by electricity prices (PPA), electrolyser CAPEX, and import prices (NH_3). $\text{LCOH}_{\text{electrolysis}}$ is most sensitive to domestic electricity costs and investment levels, while $\text{LCOH}_{\text{import}}$ depends almost entirely on the external NH_3 price. The cost gap between electrolysis and imports is therefore determined by a combination of these key factors.

For average system costs, grid supply capacity and electricity demand are the dominant drivers, largely due to the high costs of shortages (VoLL pricing). BESS capacity has a secondary but notable effect on system costs due to its role in reducing shortages.

In summary, affordability is mainly influenced by structural system factors (capacity, demand, and CAPEX) rather than short-term market prices, with shortages playing a central role in driving total system costs.

Key Findings of Experiment 1

Experiment 1 reveals the key factors influencing the system performance of the base case under the four A's. The table below lists the most influential parameters and key insights for each dimension, providing a clear basis for the focus of further scenario-based experiments 2 to 5.

Table 6-3: Experiment 1 - Overview of Key Sensitivity Drivers and Insights

Dimension (4 A's)	Key Drivers	Main Insight
Availability	Grid supply capacity, electricity demand, BESS capacity	System availability is highly sensitive to capacity constraints, especially grid supply, with storage offering secondary mitigation.
Accessibility	Hydrogen demand, offshore wind capacity, PPA requirement	Electrolyser share is primarily driven by hydrogen demand and wind electricity availability, with moderate price sensitivity.
Acceptability	Grid emission factor, offshore wind capacity, PPA requirement	CO ₂ emissions are dominated by the electricity mix; market prices have limited influence on emissions outcomes.
Affordability	PPA price, electrolyser CAPEX, NH ₃ import price, grid supply capacity	Hydrogen production and system costs are mainly driven by electricity prices, CAPEX, and shortage-related costs (VoLL).

6.2.2 Experiment 2: Multi-Sensitivity LCOH

This experiment explores breakeven conditions for domestic hydrogen production by jointly varying electrolyser CAPEX + O&M, PPA prices, and hydrogen import prices in the base case. This has resulted in 75 different scenarios. The goal is to map under which combinations offshore wind-based hydrogen can match or outperform imports in cost. This directly supports SQ1 and forms the basis for answering SQ2.

The results are presented in three steps: first, an in-depth analysis of the LCOH of electrolysis ($LCOH_{\text{electrolysis}}$); second, a comparison of the $LCOH_{\text{electrolysis}}$ with hydrogen import; and finally, a summary of the key findings from the experiment.

$LCOH_{\text{electrolysis}}$

Table 6-4 and Figure 6-9 below present the results of $LCOH_{\text{electrolysis}}$ in Experiment 2². Table 6-4 displays a heatmap, and Figure 6-9 complements this with a 3D surface plot, visually illustrating the combined effect of the three parameters on $LCOH_{\text{electrolysis}}$.

As hypothesis, it is expected that LCOH of electrolysis is primarily driven by its PPA price and CAPEX & O&M costs (according to Figure 6-5). The H₂ import price is expected to have little to no influence, as domestic production costs are largely independent of import market prices.

Table 6-4: Experiment 2 - Multi-sensitivity $LCOH_{\text{electrolysis}}$

PPA price (€/MWh)	H2 import price (€/kg)	CAPEX + O&M (€/kWe)				
		0	108	217	325	433
40	4	0.12	2.83	5.55	8.26	10.97
	6	2.75	4.16	5.57	6.98	8.39
	8	3.53	4.71	5.88	7.05	8.23
	10	3.74	4.87	6	7.13	8.26
	12	3.79	4.91	6.03	7.16	8.28
80	4	5.58	8.29	11.01	13.72	16.43
	6	5.59	7	8.41	9.82	11.23
	8	5.89	7.07	8.24	9.41	10.59
	10	6.02	7.15	8.28	9.41	10.54
	12	6.05	7.17	8.29	9.42	10.54
120	4	11.04	13.76	16.47	19.18	21.89
	6	8.43	9.84	11.25	12.66	14.08
	8	8.26	9.43	10.61	11.78	12.95
	10	8.29	9.42	10.55	11.68	12.81
	12	8.31	9.43	10.56	11.68	12.8

² Note: The independent parameter values have been rounded to the nearest whole number. For unrounded values, see Appendix D.

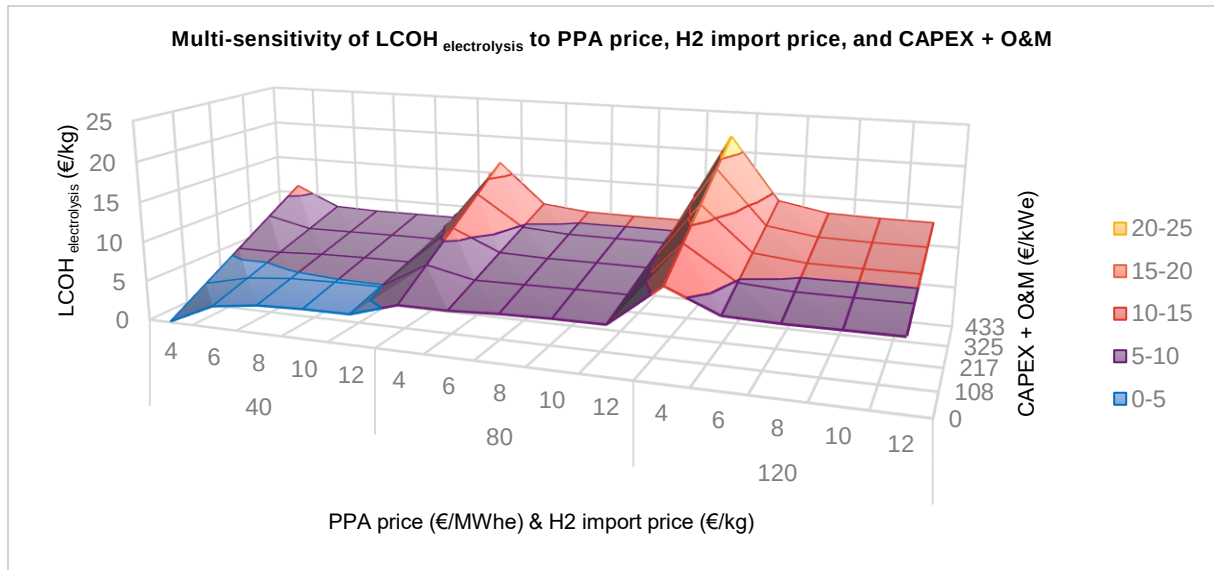


Figure 6-9: Experiment 2 - Multi-sensitivity $LCOH_{electrolysis}$

From the above results, the following conclusions can be drawn:

- PPA price indeed has a strong individual impact on $LCOH_{electrolysis}$, confirming the hypothesis. Across all scenarios, higher PPA prices lead to large increases in $LCOH_{electrolysis}$. At €40/MWh, values remain low (€3–8/kg), while at €120/MWh, they rise to €8–14/kg, regardless of other parameters.
- CAPEX + O&M reductions also provide expected cost benefits. Lower values consistently reduce $LCOH_{electrolysis}$, especially at lower PPA price levels. However, at high PPA price (€120/MWh), $LCOH_{electrolysis}$ stays high (>€8–11/kg), even with minimal CAPEX, showing the electricity costs are the main driver. This reflects the base case assumption in which €80/MWh represents the average day-ahead market price. PPAs with higher prices force electrolyzers to produce hydrogen at a loss even during ‘cheap’ hours, while the option to resell electricity provides only limited relief.
- In most scenarios (between €8–12/kg), the H_2 import price has only a marginal effect on $LCOH_{electrolysis}$ as imports remain necessary to meet residual demand not met by domestic production, regardless of costs. However, a clear exception occurs from €6/kg downwards, which is particularly noticeable at €4/kg, where $LCOH_{electrolysis}$ rises sharply for almost all PPA and CAPEX levels. This peak reflects a tipping point at which it becomes more economically efficient to resell PPA electricity instead of converting it to hydrogen. The effect becomes stronger under high PPA levels, as shown by the rising peaks, highlighting the dominant role of electricity costs in $LCOH_{electrolysis}$.

Full Load Hours and Domestic Share

As shown in Appendix E.2, the installed capacities of electrolysis and NH_3 cracking remain fixed at 3.7 GWe and 3.6 GW H_2 , respectively, across all scenarios in this experiment. Furthermore, PPA price and CAPEX + O&M have no effect on the number of FLHs of electrolysis and NH_3 cracking in this experiment. In contrast, the hydrogen import price does affect FLHs and domestic electrolyser hydrogen share. Therefore, only these indicators are presented below against varying import price levels.

As hypothesis, it is expected a tipping point in both FLHs and electrolyser share with respect to the hydrogen import price: below a certain threshold, cheap imports suppress domestic production, while above it, higher prices boost electrolyser share until system constraints cause it to stabilise.

Table 6-5: Experiment 2 - Impact of H2 import price on FLH & Domestic Electrolyser H₂ Share

H2 import price (€/kg)	FLH Electrolysis hours	FLH NH3 Cracking hours	H ₂ -E Share -
4	2242	7182	0.182
6	4308	5707	0.35
8	5180	5084	0.421
10	5378	4942	0.437
12	5414	4917	0.44

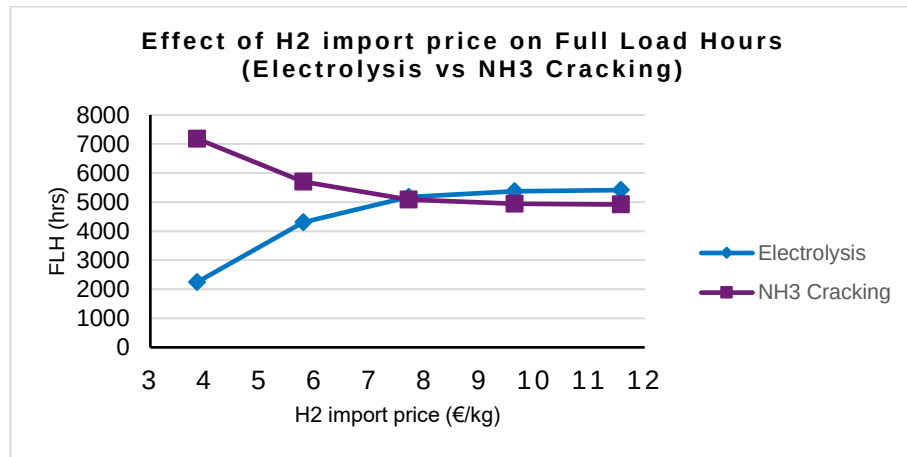


Figure 6-10: Experiment 2 - Impact of H2 import price on FLH

The results confirm the hypothesised tipping point, showing a sharp initial increase in electrolyser FLHs from ~2,200 hours at €4/kg to over 5,400 hours at €12/kg, followed by a flattening at higher import prices. An opposite pattern is observed for NH₃ cracking, where FLHs fall from ~7,100 to ~4,900 hours before stabilising. Table 6-5 further reflects this shift, with electrolyser share nearly doubling from 0.18 to 0.44. These patterns support the hypothesis that low import prices (€4–6/kg) suppress domestic share and raise LCOH_{electrolysis}, while higher prices improve domestic share but maintain a continued reliance on imports.

LCOH Difference

Table 6-6 and Figure 6-11 below present the results of LCOH Difference in Experiment 2. The table shows a heatmap, while the figures display separate plots for each PPA price level. In the figures, the black line represents the 0-contour, the tipping point where LCOH_{electrolysis} becomes cost-competitive with imported hydrogen (LCOH_{import}). Values below zero (left/above the black line) indicate domestic production is cheaper than imports; values above zero indicate the opposite.

As hypothesis, it is expected that the LCOH Difference is primarily driven by the import price, with the PPA price and CAPEX & O&M costs having a secondary but still notable and roughly equal influence (according to Figure 6-7).

Table 6-6: Experiment 2 – Multi-sensitivity LCOH Difference

PPA price (€/MWh)	H2 import price (€/kg)	CAPEX + O&M (€/kWe)				
		0	108	217	325	433
40	4	-4.79	-2.08	0.64	3.35	6.06
	6	-4.13	-2.72	-1.31	0.1	1.51
	8	-5.3	-4.13	-2.95	-1.78	-0.61
	10	-7.02	-5.89	-4.76	-3.63	-2.5
	12	-8.9	-7.78	-6.66	-5.53	-4.41
80	4	0.67	3.39	6.1	8.81	11.52
	6	-1.29	0.12	1.53	2.94	4.35
	8	-2.94	-1.76	-0.59	0.58	1.76
	10	-4.75	-3.62	-2.49	-1.36	-0.23
	12	-6.64	-5.52	-4.39	-3.27	-2.15
120	4	6.13	8.85	11.56	14.27	16.98
	6	1.55	2.96	4.37	5.78	7.2
	8	-0.57	0.6	1.77	2.95	4.12
	10	-2.47	-1.34	-0.21	0.92	2.05
	12	-4.38	-3.26	-2.13	-1.01	0.11

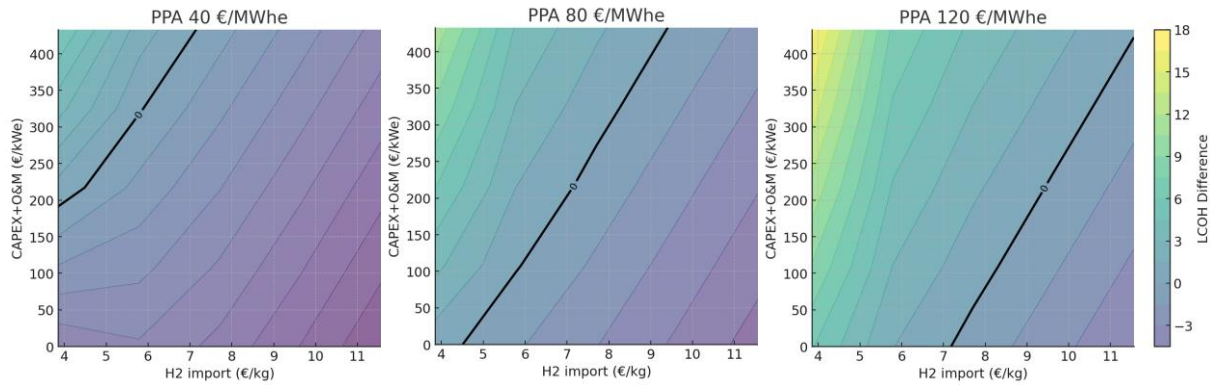


Figure 6-11: Experiment 2 – Multi-sensitivity LCOH Difference by PPA level

From the above results, the following conclusions can be drawn:

- PPA = 40 €/MWh: The hypothesis is largely supported—import price is clearly the main driver of cost competitiveness. Import prices above €7/kg make electrolysis competitive across all CAPEX levels, while low import prices ($\leq$ €4/kg) are only competitive when CAPEX is low ($<$ €200/kWe).
- PPA = 80 €/MWh: Import price remains the dominant factor, but the influence of CAPEX becomes more balanced. The tipping point occurs at roughly mid-range values for both import price and CAPEX. Notably, even with CAPEX = €0/kWe, electrolysis is still not competitive when the import price is below €4.5/kg.
- PPA = 120 €/MWh: Import price again dominates, but high PPA levels mean cost competitiveness is only achievable when both import price and CAPEX are favourable. At medium to low import prices ($\leq$ €8/kg), electrolysis is not competitive under any CAPEX scenario.

In summary, the results confirm that the import price—an external factor (X) in the XLRM framework—is the primary driver of LCOH Difference, while PPA price and CAPEX & O&M—both policy levers (L)—act as secondary but still notable influences. For each PPA price, there is a tipping point, defined by a combination of import price and CAPEX, at which electrolysis becomes cost-competitive. Low PPA prices and/or high import prices are essential for competitiveness, while high CAPEX and especially high PPA prices weaken it significantly. This underlines the importance of policy levers in shifting competitiveness thresholds, even when the dominant driver is an external market factor.

Key Findings of Experiment 2

Experiment 2 assesses the cost-competitiveness of domestic hydrogen production by jointly varying electrolysis CAPEX + O&M, PPA prices, and hydrogen import prices. Across 75 scenarios, it identifies key breakeven points where offshore wind-based hydrogen can match or outperform imports. The findings highlight the dominant role of PPA prices, with low PPA and sufficiently high import prices being essential for the cost-competitiveness of domestic hydrogen. The summary table below outlines the main cost drivers and competitiveness thresholds.

Table 6-7: Experiment 2 - Summary of Cost-Competitive Conditions in Base Case Scenario

PPA price (€/MWh)	Cost-Competitive Tipping Point ($LCOH_{\text{electrolysis}} < LCOH_{\text{import}}$)			
	Separate		Midpoint of Trade-off	
	H ₂ import price (€/kg)	CAPEX + O&M (€/kWe)	H ₂ import price (€/kg)	CAPEX + O&M (€/kWe)
40	7 or higher	200 or lower	6 or higher	& 325 or lower
80	9.5 or higher	-	7.5 or higher	& 225 or lower
120	12 or higher	-	9.5 or higher	& 225 or lower

6.2.3 Experiment 3: System Flexibility & Resilience

This experiment assesses how flexible and resilient the base case system remains under combined variations in electricity and hydrogen demand, supply capacity (wind/grid), and electricity storage. The analysis focuses on system availability (LOLE) and system operability (Installed Capacities, FLHs, and Cycle Rates). A total of 200 different scenarios were simulated to explore a broad range of demand and supply combinations. The primary objective is to understand under which conditions domestic hydrogen production maintains a stable contribution to the energy system, directly addressing SQ2.

System Availability (LOLE)

Figures 6-12 and 6-13 show boxplots of the LOLE results for Experiment 3, illustrating the distribution across varying BESS and grid supply capacities. EENS shows similar patterns and is, therefore, omitted from the main text (see Appendix E.3 for the complete set of results).

As hypothesized, system availability is expected to be driven mainly by the maximum grid supply capacity and electricity demand, with smaller contributions from OSW installed capacity and BESS capacity (according to Figure 6-2).

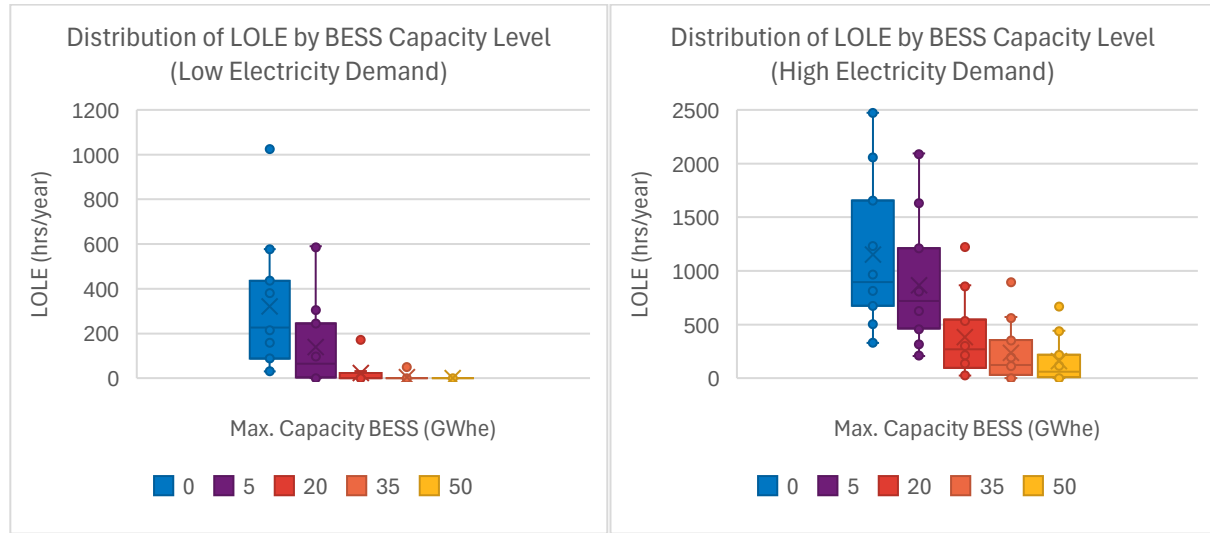


Figure 6-12: Experiment 3 – Impact of BESS Capacity and Electricity Demand on LOLE

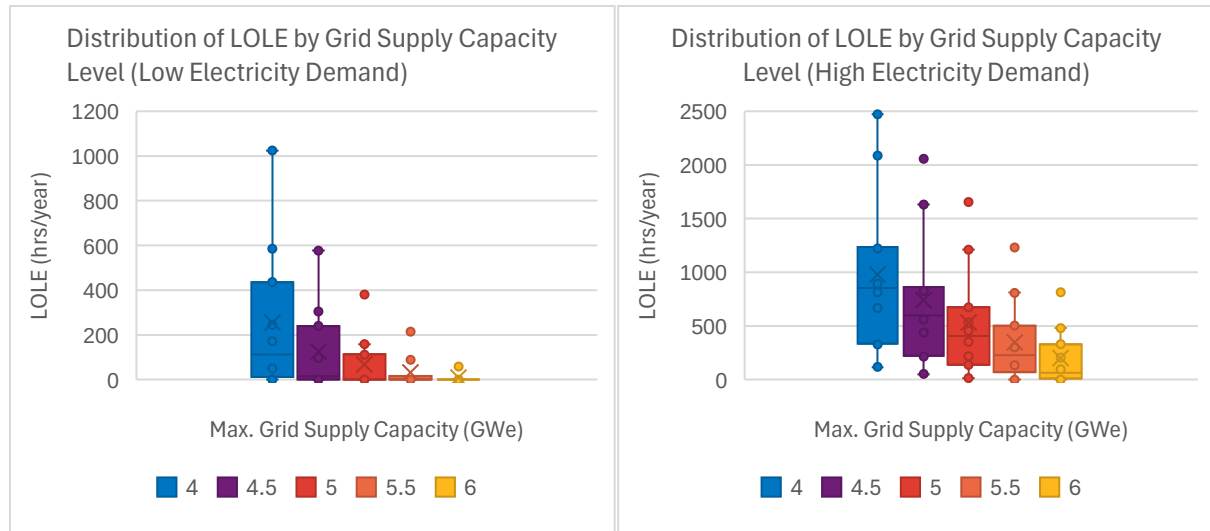


Figure 6-13: Experiment 3 – Impact of Grid Supply Capacity and Electricity Demand on LOLE

From the above results and complete EENS/LOLE heatmaps in Appendix E.3, the following conclusions can be drawn:

- Hydrogen demand has negligible impact on LOLE (and EENS), confirming the hypothesis that shortages are driven by electricity constraints rather than hydrogen demand, which is fully met via flexible imports.

- Electricity demand is a dominant driver: higher demand consistently increases LOLE, especially under low wind supply conditions, in line with the hypothesis.
- BESS capacity has a stronger effect than anticipated. While the hypothesis assumed only a modest contribution, results show that even moderate increases (0 to 5 GWhe) significantly reduce LOLE. At 20–50 GWhe, shortages nearly disappear under low demand—even with a grid supply capacity as low as 4 GWe. Under high demand, only scenarios with both 35–50 GWhe BESS and 5.5–6 GWe grid supply capacity, combined with peak wind capacity, achieve LOLE < 11 hrs/year.
- Grid supply capacity has a similar mitigating effect as BESS capacity, underlining their complementary roles in reducing shortage hours. However, as discussed earlier in Section Grid Constraints and Infrastructure Developments, future grid capacity is uncertain due to congestion and is therefore classified as an external factor (X) in the XLRM framework. This reinforces the importance of large-scale electricity storage and OSW capacity—both classified as policy levers (L)—to ensure long-term system availability.

System Operationality

Electrolysis

As shown in Appendix E.3, the FLHs of electrolysis in this experiment ranges from ~3800 to ~5400 hours/year, depending on the balance between supply and demand. Under low electricity demand, FLHs remain high (~5000–5300 hours), with only small improvements from additional BESS or grid capacity. In high electricity demand scenarios, FLHs drop significantly—especially with low wind capacity (7.4 GWe) and limited grid supply capacity (4 GWe)—to around 3800 hours.

To consistently achieve FLHs above 4,500 hours, at least 5 GWe grid capacity is required. With sufficient hydrogen demand, high wind availability, and strong flexibility (50 GWhe BESS, 6 GWe grid capacity), FLHs can reach ~5,400 hours. Generally, BESS capacity increases the FLH only when there is a surplus of electricity available, while grid capacity plays a larger role when electricity demand is high and wind capacity is low. In this way, the two complement each other in increasing the utilisation of electrolysis.

Appendix E.3 also confirms, consistent with Experiment 2, that lower LCOH from electrolysis is closely correlated with higher FLHs. In this experiment, LCOH_{electrolysis} ranges from €10.5 to €12.5/kg, with the lowest values occurring in scenarios achieving the highest FLHs.

Storage

Appendix E.3 shows that BESS capacity is optimised to its maximum in almost all scenarios, except where surplus electricity or demand is limited. Cycle rates decrease as installed capacity increases—a typical pattern where larger storage volumes cycle less often but handle more per cycle. Cycle rates are higher under high wind capacity (average 363 cycles/year) compared to low wind (average 289 cycles/year), reflecting greater surplus generation opportunities. BESS is primarily used to absorb short-term electricity surpluses, increasing system flexibility during daily and weekly fluctuations.

Salt cavern hydrogen storage is deployed only in high-wind and low hydrogen-demand scenarios, reaching up to ~435 GWh with ~20 cycles/year. When hydrogen demand is high, caverns remain largely unused as hydrogen is consumed directly and is optimally provided by the NH₃ cracker.

In summary, BESS provides short-term flexibility, while salt caverns act as long-term backup during extended surpluses, mainly driven by PPA obligations and limited resale opportunities due to higher overall system costs.

Key Findings of Experiment 3

Experiment 3 evaluates the impact of electricity and hydrogen demand, supply capacities, and storage on system availability and operational flexibility. The results show that electricity demand and grid/BESS capacity are the dominant drivers of system stability, while hydrogen demand remains largely irrelevant due to flexible imports. Sufficient grid (≥5.5 GWe) and BESS (≥35–50 GWhe) capacity are essential to limit shortages (LOLE) and maintain stable electrolysis utilisation (≥4500 FLH). Salt cavern storage only plays a minor role under low hydrogen demand and high wind availability.

6.2.4 Experiment 4: Fixed H2 Import

This experiment investigates the impact of fixed hydrogen import capacity on the optimal installed capacity of electrolysis. Unlike previous experiments where import capacity is optimised, this scenario assumes fixed import levels, reflecting potential geopolitical or logistical constraints where import supply cannot be controlled. The aim is to determine how domestic production (via electrolysis) deals with varying levels of imports under different OSW installed capacities. A total of 27 scenarios were analysed, varying NH₃ Cracker capacity (0–8 GW H₂) and OSW capacity (7.4, 13.4, and 19.4 GWe). The experiment is conducted under high electricity demand, moderate hydrogen demand (7.2 GWh H₂/hour), and maximum BESS capacity (50 GWhe). This combination of assumptions, ensures that the analysis captures conditions where trade-offs between domestic hydrogen production and imports are impactful. This experiment contributes to SQ2 by exploring how the domestic system adjusts to fixed hydrogen imports while maintaining system adequacy.

Installed Capacities

Table 6-8 and Figure 6-14 below present the effect of installed capacities (ICs) of NH₃ cracking and OSW on the corresponding optimal installed capacity of electrolysis in Experiment 4.

As hypothesis, it is expected that increasing NH₃ cracker capacity will reduce the optimal installed capacity of electrolysis, as imports substitute domestic production. This effect is anticipated to be strongest when OSW capacity is high, since surplus wind electricity enables greater domestic production when imports are limited.

Table 6-8: Experiment 4 - Impact of fixed H2 Import & OSW Capacity on Optimal IC Electrolysis

OSW Installed Capacity (GWe)	Installed Capacity NH3 Cracking (GW H2)								
	0	1	2	3	4	5	6	7	8
7.4	6.45	6.45	6.45	6	5.79	6.41	5.82	0.88	0
13.4	11.59	11.59	12.26	12.19	12.19	7.38	3.36	0.53	0
19.4	17.97	17.84	17.74	13.37	9.05	5.42	2.82	0.47	0

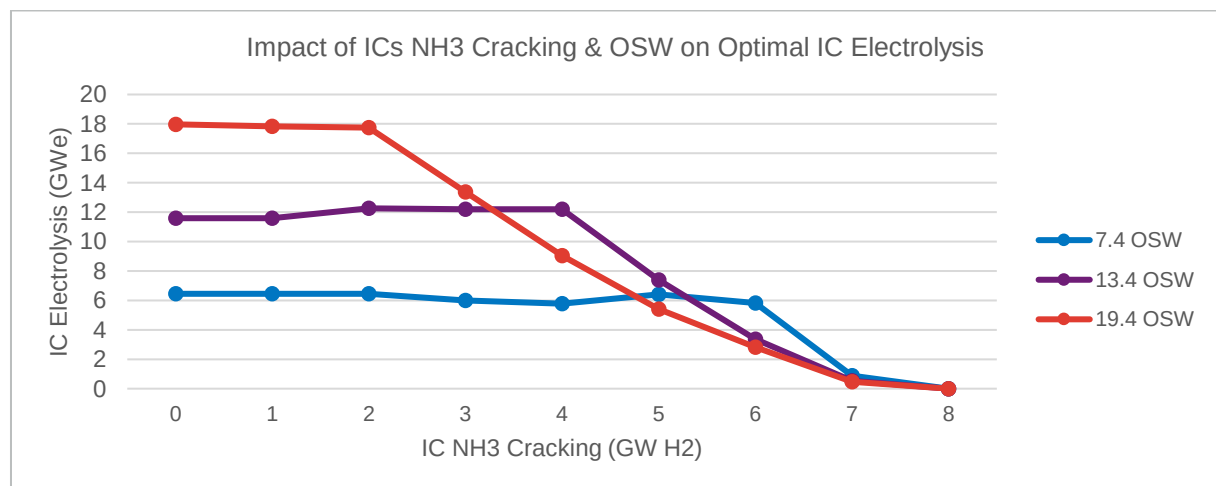


Figure 6-14: Experiment 4 - Impact of fixed H2 Import & OSW Capacity on Optimal IC Electrolysis

The results confirm the hypothesised inverse relationship between NH₃ cracker capacity and optimal electrolysis capacity:

- Across all OSW capacity levels, electrolysis remains stable up to a NH₃ cracker capacity threshold—~6 GW H₂ at 7.4 GWe OSW, ~4 GW H₂ at 13.4 GWe, and ~2 GW H₂ at 19.4 GWe—after which it declines sharply. These thresholds align with the hypothesis: higher OSW capacity supports greater domestic production until imports meet demand, at which point electrolysis is displaced.
- At 8 GW H₂ cracker capacity, electrolysis drops to zero in all OSW scenarios, as the fixed hydrogen demand (~7.2 GWh H₂/hour) can be fully covered by imports.

These thresholds mark cost-optimal balances between imports and domestic production, also reflected in LOLE, EENS, and Avg. SC (see Appendix E.4). Beyond these points, additional imports yield diminishing returns in terms of system adequacy and cost. Even under high OSW scenarios, large-scale imports can displace domestic produced hydrogen, highlighting the need to balance domestic hydrogen investments with strategic import decisions.

PPA Resale

The table below presents the effect of installed capacities of NH₃ cracking and OSW on the corresponding average resale of PPA electricity from electrolysis.

As hypothesised, it is expected that PPA electricity resale from electrolysis will rise with increasing NH₃ cracker capacity, as fixed imports replace domestic hydrogen and free up contracted electricity for resale—an effect expected to be stronger at higher OSW capacities due to greater surplus wind electricity.

Table 6-9: Experiment 4 - Impact of fixed H₂ Import & OSW Capacity on resale of PPA Electricity

OSW Installed Capacity (GWe)	Avg. Buy & Sell PPA Electricity (GWe/hour)								
	0	1	2	3	4	5	6	7	8
7.4	1.03	1.03	1.03	1.03	1.04	1.05	1.36	1.93	1.99
13.4	1.10	1.11	1.11	1.44	1.82	2.37	2.55	2.66	2.67
19.4	1.51	1.76	2.08	2.48	2.64	2.71	2.79	2.83	2.84

The results in Table 6-9 confirm the hypothesised relationship. While the optimal installed capacity of electrolysis decreases with higher NH₃ cracker capacity (as described in the previous section), PPA electricity resale increases significantly as imports rise. This reflects cost-optimisation: when part of the domestic hydrogen demand is met by imports, surplus PPA electricity can be sold back to the grid—either to cover system shortages or when DA market prices exceed PPA contract prices—reducing total system costs.

This resale mechanism also has a substantial impact on LCOH_{electrolysis} (see Appendix E.4), even leading to negative values from ~6 GW H₂ cracker capacity onwards. Although such negative values are not realistic in practice, it highlights the potential influence of PPA resale on the business case for electrolysis.

Similar to earlier findings, a tipping point is observed for each OSW capacity level, beyond which further NH₃ imports shift electrolysis from hydrogen production towards maximising PPA electricity resale. This highlights the dual role of electrolysis in the system: as both hydrogen producers and flexible electricity market participants.

Hydrogen Storage

While hydrogen storage in salt caverns played only a minor role in previous experiments, this experiment shows a more active and dynamic function. In addition to the expected increase in BESS cycle rates—driven by more frequent wind electricity surpluses and higher hydrogen imports (see Appendix E.4)—hydrogen storage becomes more actively involved in balancing the system.

Appendix E.4 indicates that for each OSW capacity, there is an optimal range of salt cavern capacity and corresponding cycle rates, both highest at moderate hydrogen import levels. At low imports (≤ 3 GW H₂) and low OSW capacity, domestic hydrogen production is too limited to utilise storage. At high imports (≥ 5 GW H₂) and high OSW capacity, domestic production drops, reducing storage utilisation as both optimal capacity and cycle rates decline.

Overall, hydrogen storage contributes most effectively at moderate import levels, when domestic production remains high enough to exploit available storage capacity.

Key Findings of Experiment 4

Experiment 4 assesses the effect of fixed hydrogen import capacity on domestic electrolysis under varying OSW supply. Results show a clear trade-off: higher imports reduce optimal electrolysis capacity, with full displacement at a certain level of hydrogen import capacity (in this experiment: ≥ 8 GW H₂). Higher OSW (up to 19.4 GWe) delays this decline but only up to an import-dependent threshold. At high imports, electrolysis shifts to PPA resale, lowering LCOH_{electrolysis} but reducing hydrogen output. Salt cavern storage plays a particularly important role at moderate import levels. Overall, the results emphasise the importance of strategically aligning domestic production capacity, import reliance, and storage opportunities.

6.2.5 Experiment 5: Extreme H2 Supply

This experiment stress-tests the system under extreme hydrogen supply conditions. A total of 96 scenarios are analysed for both the years 2022 and 2024, using DA electricity prices, electricity demand profiles, and OSW capacity data from each respective year. 2022 specifically reflecting a period of extreme market volatility caused by the energy crisis (see Appendix D.2). The scenarios systematically vary five key parameters: NH₃ cracker capacity (0 or optimised GW H₂), hydrogen demand (low or high), OSW capacity (7.4, 13.4, or 19.4 GWe), electrolyser PPA requirement (0% or 50% of OSW generation), and electrolyser DA market access to buy electricity (0% or 50% of its capacity). All cases are modelled under high electricity demand with optimised BESS capacity (max. 50 GWhe). The experiment identifies key system bottlenecks and operational thresholds, directly contributing to SQ2.

LCOH_{electrolysis} and Full Load Hours

The table and figure below present the effect of extreme H2 supply scenarios on LCOH_{electrolysis} for the historic years 2022 and 2024.

As hypothesis, extreme hydrogen supply scenarios are expected to significantly affect both LCOH_{electrolysis} and electrolyser FLHs, with market volatility amplifying these effects. In the volatile year 2022, DA market access—particularly when combined with PPAs—is expected to trigger large LCOH_{electrolysis} swings due to electricity resale opportunities. In the more stable year 2024, these effects are expected to be smaller, with LCOH_{electrolysis} more closely tracking underlying price levels and utilisation patterns.

Table 6-10: Experiment 5 - Impact of Extreme H2 Supply Scenarios on LCOH_{electrolysis}

H2 Import			2022				2024			
			No		Optimised		No		Optimised	
PPA-requirement	DA access	IC OSW (GWe) \ H2 Demand	Low	High	Low	High	Low	High	Low	High
0%	0%	7.4	0	0	0	0	0	0	0	0
		13.4	0	0	0	0	0	0	0	0
		19.4	0	0	0	0	0	0	0	0
	50%	7.4	18.6	18.6	41.2	41.2	9.7	9.7	9.9	9.9
		13.4	18.8	18.8	33.4	32.2	9.2	9.1	9.4	9.3
		19.4	18.1	18.9	31.4	29.9	10.2	9.1	10.3	9.1
50%	0%	7.4	10.4	10.4	-17	-17	10.7	10.7	10.9	10.9
		13.4	10.7	10.7	-11.3	-10.4	10.6	10.6	10.6	10.6
		19.4	9.6	10.7	-5.4	-4.1	11.1	10.6	11.2	10.6
	50%	7.4	13.7	13.9	-2.4	3.1	12.2	12.6	11.7	12.4
		13.4	12.8	14.6	-2.4	6.5	11.5	11.2	11.5	11.1
		19.4	11.7	14.8	6.1	8.5	14.5	10.8	14.5	10.8

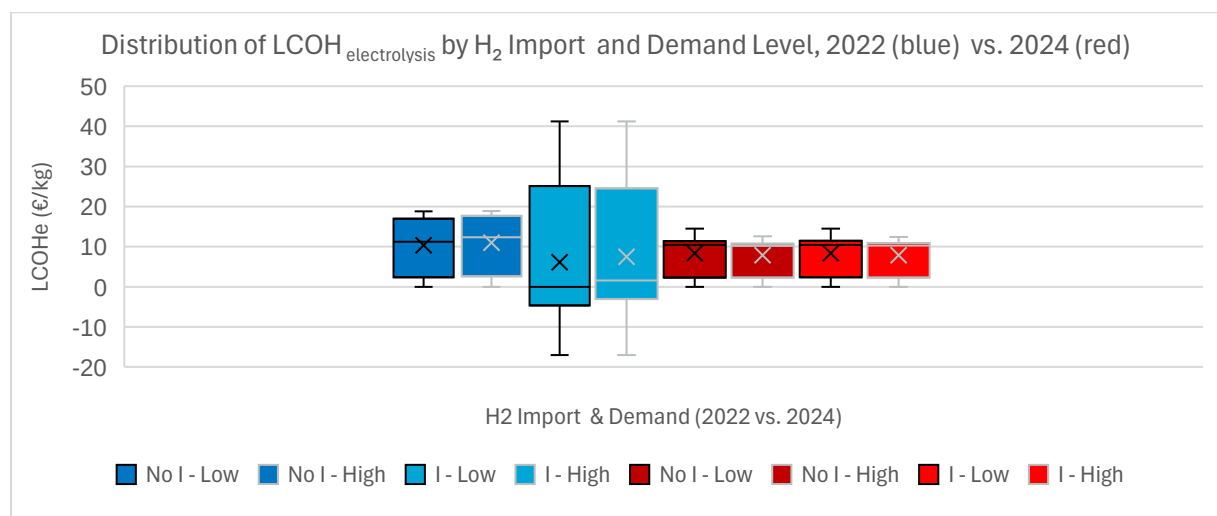


Figure 6-15: Experiment 5 - Impact of H2 Import, H2 Demand, and Historic Year on LCOH_{electrolysis}

The results in Appendix E.5 and the table and figure above show a clear contrast in LCOH_{electrolysis} between 2022 and 2024:

2022 – extreme volatility

The results confirm the hypothesis: in a volatile year, DA market access combined with PPAs leads to extreme LCOH_{electrolysis} variation (-17 to 41.2 €/kg), especially in scenarios with optimised hydrogen imports.

- LCOH_{electrolysis} ranges from very high (€30–40/kg) in scenarios without PPA requirements but with DA market access, to very low (-€4 to -€17/kg) in scenarios with PPA requirements but without DA market access.
- These extremes result from the severe DA price volatility in 2022, highlighting the need and stabilising effect of PPA contracts. However, the model's perfect foresight leads to extreme resale profits, where cheap PPA electricity is not used for hydrogen production but sold back into the market, resulting in negative LCOH_{electrolysis}.
- Furthermore, Appendix E.5 shows low electrolyser utilisation (800–1250 FLHs), despite large installed capacities (~4–10 GWe). This indicates that electrolysers, with their PPAs, are used opportunistically to decrease the systems' costs: producing hydrogen during low-price periods and acting as power trading assets during high-price intervals, rather than serving as consistent hydrogen producer.
- This presents a potential hydrogen supply risk, where PPA contracts could be exploited for arbitrage, especially by energy companies owning electrolysers, such as Eneco. This model outcome warrants further investigation into how PPA contracts are structured and regulated, in particular around resale of PPA electricity.

2024 – stable market dynamics

In the more stable 2024 market, the hypothesis is again supported but in a moderated form.

- The trend is almost the opposite. DA market access alone results in the lowest LCOH_{electrolysis} (9.1-10.3 €/kg), while PPAs without DA access leads to higher LCOH_{electrolysis} (10.6-11.1 €/kg), and PPAs in combination with DA access results in the highest LCOH_{electrolysis} (10.8-14.5 €/kg).
- Furthermore, Appendix E.5 shows high electrolyser utilisation (~4600 to 7000 FLH) in PPA-only or DA-only scenarios, despite large installed capacities (~4–10 GWe).
- This reflects a more stable market in 2024, where direct market access becomes more favourable than fixed-price PPAs. However, given future price uncertainties, PPAs remain a risk-hedging strategy.

Impact of DA access on electrolyser capacity

- For both historic years, electrolyser capacity remains consistently high (~4 to 10 GWe) when either no PPA + 50% DA access or 50% PPA + no DA access is applied, indicating that overall system availability drives capacity decisions rather than the electricity prices.
- For both historic years, scenarios with 50% PPA + 50% DA access show the highest capacity (~6 to 17 GWe), but also a higher LCOH_{electrolysis} due to lower FLHs. This reflects a model system trade-off: higher LCOH_{electrolysis}, but lower overall system costs due to better integration of electricity in the system.

Key Findings of Experiment 5

The table below summarises the main outcomes of Experiment 5, showing how market volatility, PPA obligations, and DA market access affect LCOH_{electrolysis} and electrolyser performance under extreme supply scenarios.

Table 6-11: Experiment 5 - Key Findings in Extreme Scenarios

Finding	Summary
LCOH_{electrolysis} volatility	Extreme LCOH _{electrolysis} spread in 2022 (-17 to 41 €/kg); more stable in 2024 (9–14.5 €/kg).
DA access impact	Providing electrolysers with (additional) DA market access lowers overall system costs but raises LCOH _{electrolysis} .
PPA role	PPAs help in volatile markets but raise LCOH _{electrolysis} in stable markets due to fixed price inflexibility.
Utilisation	Electrolysers showed low utilisation in 2022 (<1250 FLH) under optimised hydrogen import scenarios due to a focus on PPA electricity resale ; In contrast, utilisation was significantly higher (~5000 FLH) in 2024 for both no-import and optimised-import cases, supported by stable market conditions.
Policy risk	Resale opportunities of PPA electricity can undermine domestic hydrogen production goals, especially in volatile years.

6.2.6 Cross-Experiment Analysis

This section compares key model outcomes across the full set of exploratory experiments. The analysis highlights patterns in cost-competitiveness and system robustness, and reflects on how both policy levers (L) and external uncertainties (X)—as defined in the XLRM framework—influence the model outcomes. The exploratory setup, consistent with the principles of Exploratory Modelling and Analysis (EMA), allows for the identification of both robust and vulnerable configurations across a wide scenario space.

While Experiment 1 provided useful insights through one-at-a-time sensitivity testing, is excluded from this analysis as it does not follow a scenario-based structure and is therefore not directly comparable to the EMA experiments (2–5).

Cost-Competitiveness

Figures 6-16 and 6-17 present the distributions of the levelized cost of hydrogen (LCOH) from electrolysis, hydrogen imports, and their difference across Experiments 2 to 5 and the entire scenario ensemble.

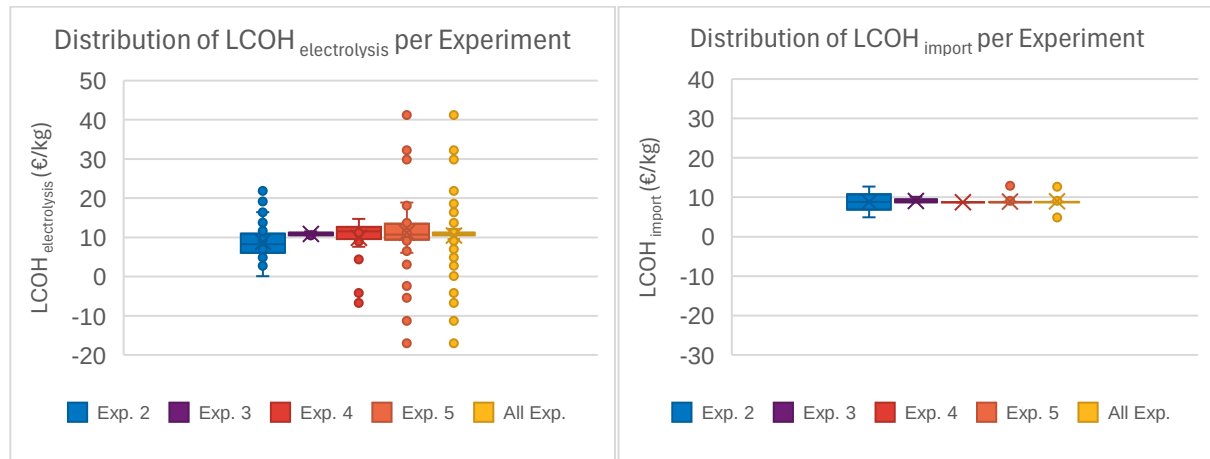


Figure 6-16: Distribution of $LCOH_{electrolysis}$ (left) & $LCOH_{import}$ (right) per Experiment

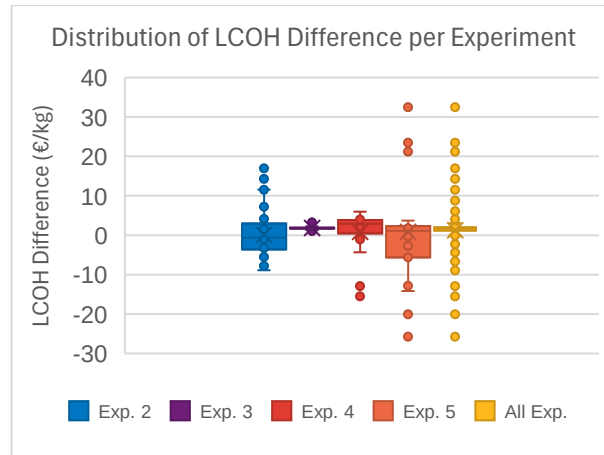


Figure 6-17: Distribution of $LCOH$ Difference per Experiment

Out of 331 scenarios³, only 60 cases (18%) resulted in a negative LCOH Difference, meaning electrolysis was cheaper than imports. Remarkably, 42 of these occur in Experiment 2 (of 75 scenarios), which specifically explores combinations of the policy levers (L) CAPEX and PPA price, alongside the external uncertainty (X) of import price. This confirms that these levers are most influential in achieving cost-competitive domestic hydrogen.

In Experiments 3, 4, and 5 cost-competitive outcomes are rare and mostly result from PPA electricity resale, which artificially lowers $LCOH_{electrolysis}$ under certain market conditions. However, such cases are less robust and highly dependent on favourable or volatile electricity markets.

³ Note: Only scenarios (331 out of 398) in which either electrolyzers or NH_3 crackers produce a non-zero hydrogen output have been included.

System Robustness

Figures 6-18 and 6-19 show the distribution of Loss of Load Expectation (LOLE) and Full Load Hours (FLH) for electrolysis across Experiments 2 to 5. These KPIs provide insight into the system's robustness; operational stability and effective utilisation of electrolysis under varying uncertainty combinations.

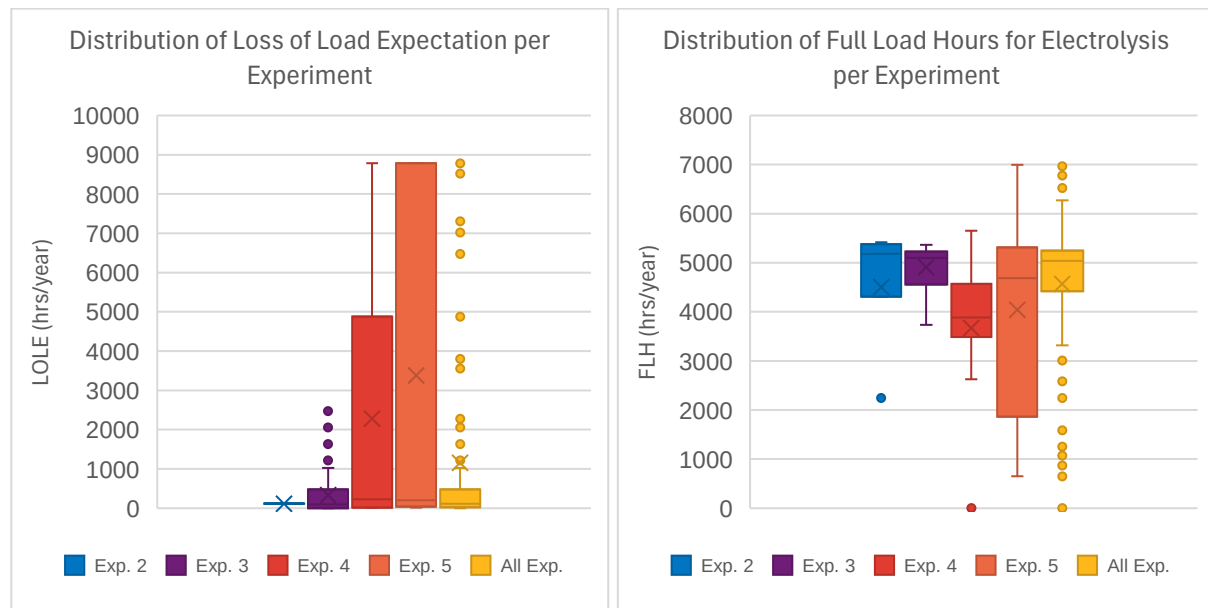


Figure 6-18: Distribution of LOLE (left) & FLHs for Electrolysis (right) per Experiment

Across the full set of 398 scenarios, only 100 cases (25%) achieve LOLE below 20 hours/year. These low-LOLE outcomes are mostly concentrated in Experiment 3 (72 cases in 200 scenarios), which varies grid supply, wind capacity, electricity/hydrogen demand, and storage. This underlines the importance of energy system flexibility in maintaining reliability. In contrast, Experiments 4 and 5 show very high LOLE values (medians > 4000 hours), driven by scenarios with restricted import capacity. These reflect the system's vulnerability to both external supply and demand (X), and limited operational flexibility (L).

In parallel, the FLH distribution illustrates how often electrolysis is effectively utilised in the model. Out of 374 scenarios, 270 cases (72%) achieved FLHs above 4500 hours/year, indicating that high utilisation levels are feasible under a broad range of conditions. Experiment 2 delivers the highest median FLH (~5000 hours/year), driven by the advantages of PPAs. By contrast, Experiment 5 shows a broader and more volatile FLH range—from near zero to 7000 hours/year—reflecting extreme variations in electricity availability, demand, and market conditions. This confirms that X-factors such as H₂ demand and wind availability, alongside L-factors like DA market access and PPA requirements, play a decisive role in electrolyser performance.

Key Findings of Cross-Experiments

Overall, these findings illustrate the value of EMA in mapping the boundaries of robust system behaviour. While domestic hydrogen can be cost-competitive, it only occurs within a narrow region of the uncertainty space—shaped by both controllable levers (CAPEX, PPA price) and uncontrollable market conditions (H₂ import price).

System adequacy and electrolyser utilisation are similarly constrained. Reliable performance only occurs when flexible capacity (e.g., grid supply and BESS) is sufficient, and when import restrictions are limited. Outside of these conditions, the system is prone to shortages, high costs, or underutilisation. The above analysis effectively reveals these boundaries of feasibility, enabling better-informed and more resilient policy decisions.

6.3 Model Validation

Model validation involves assessing whether the outcomes produced by the computational model provide an adequate answer to the research question. In essence, this means that the model's results should align sufficiently with empirical

observations of the system being studied. However, in this case, the model represents a hypothetical system rather than one that currently exists. As a result, direct validation against real-world data is not feasible [108]. To ensure the model's structure and outcomes, several elements of the model were discussed and validated through conversations with experts from the Port of Rotterdam [93], [109], [110]. These expert insights played a key role in shaping the model and assessing its plausibility. This section, however, focuses specifically on the validation of the model's outcomes through comparison with findings from existing literature.

6.3.1 LCOH_{electrolysis}

To validate the LCOH_{electrolysis} results, the Renewable Hydrogen Cost Evaluation Tool (RHyCEET) from TNO [27] is used. Key input parameters from the Linny-R base case scenario—such as the PPA price and CAPEX + O&M—as well as output variables like full load hours and installed capacity, are gathered and applied in the RHyCEET model to compare the LCOH_{electrolysis} breakdown. The resulting comparison is shown in the figures below.

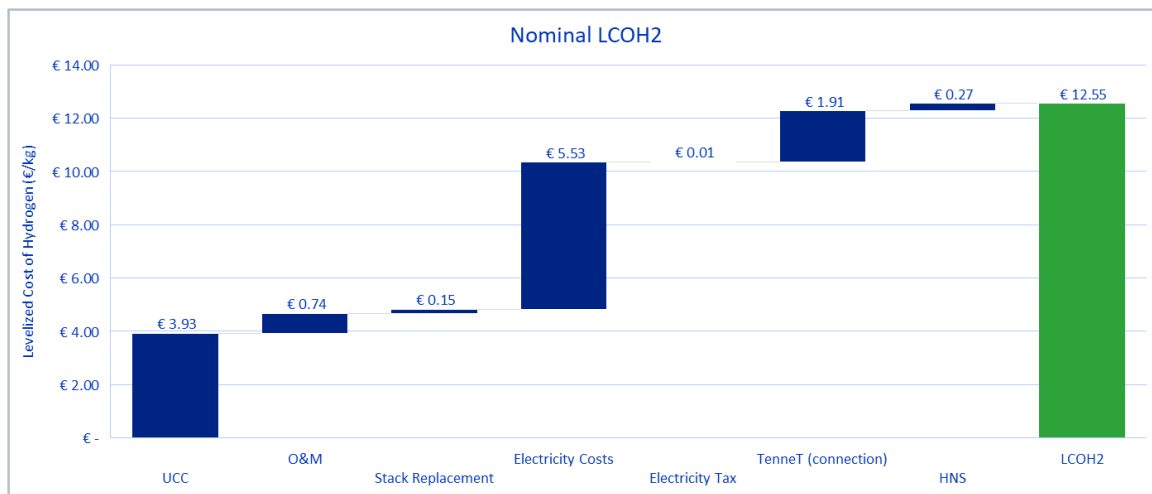


Figure 6-19: LCOH_{electrolysis} Breakdown for Base Case Values in RHyCEET [27]

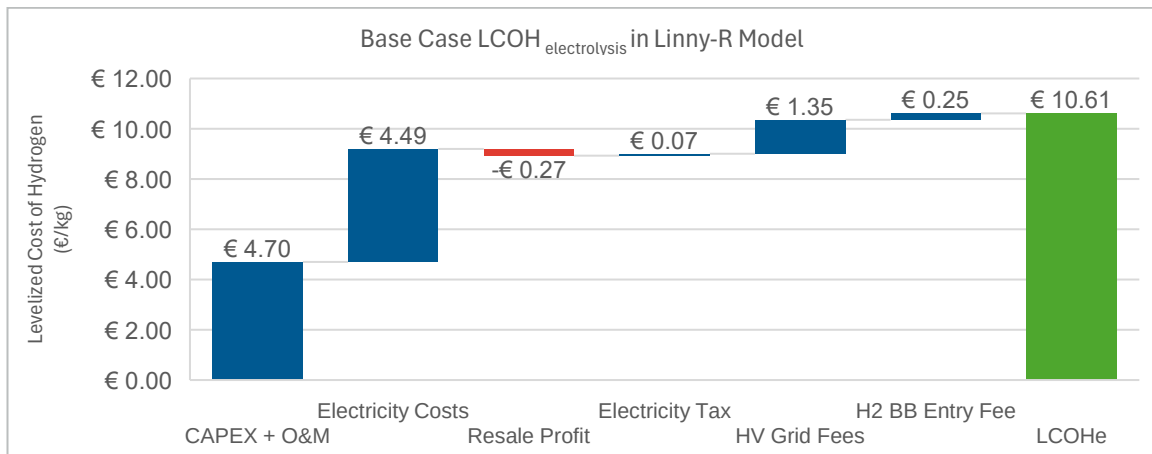


Figure 6-20: Validation - LCOH_{electrolysis} Breakdown for Base Case Scenario in Linny-R Model

Main observations:

- It is notable that both LCOH_{electrolysis} results are very similar, which is expected since most financial and technical electrolyser parameters used in the Linny-R model were taken from the TNO report [27]. The LCOH_{electrolysis} in the Linny-R model is ~€2/kg lower than in the RHyCEET model. Given that the Linny-R model simulates an entire optimised year in detail, this close alignment confirms that the LCOH_{electrolysis} calculation is well-executed.
- The CAPEX + O&M costs are nearly identical in both models: €4.70/kg in Linny-R versus €4.82/kg in RHyCEET (which includes UCC, O&M, and stack replacement).

- Electricity costs in the Linny-R model are roughly €1/kg lower than in the RHyCEET model (4.49 vs. 5.53 €/kg). This difference can be explained by the inclusion of electricity resale in the Linny-R model. Since excess electricity can be sold back to the market and, when profitable, this reduces the net electricity cost and introduces a small resale profit (-€0.27/kg).
- HV grid fees in the Linny-R model are slightly lower (€1.35 vs. €1.91). This is because, in 2024, the HV grid fee in the TNO model is still treated as a fixed amount, while from 2025 onwards, it is split into a fixed and variable component [100]. The Linny-R model accounts for this change, as discussed earlier in Section 5.5.2. As a result, the electrolyser adapts by operating more during low-cost periods, reducing the impact of variable grid fees. This shows that the ACM's intervention has a downward effect on grid costs, which is clearly reflected in the Linny-R results.
- Finally, the Hydrogen backbone entry fee aligns almost perfectly between both models.

Overall, this comparison shows a strong consistency between the models and supports the validity of the $LCOH_{\text{electrolysis}}$ calculation in Linny-R.

6.3.2 Full Load Hours

To validate the experiment results of the full load hours, Figure 6-18 shows the distribution of FLHs for electrolysis and NH_3 cracking in the Linny-R model, enabling comparison with benchmark assumptions from literature.

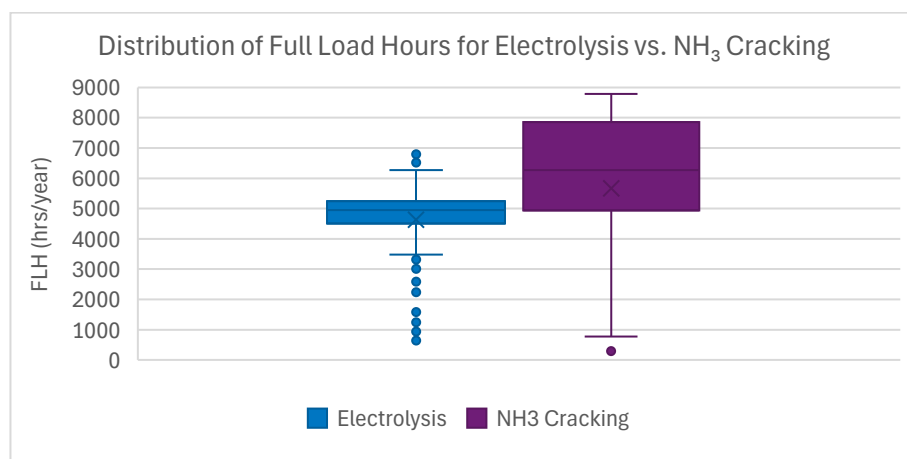


Figure 6-21: Validation – Full Load Hours in Linny-R Model

Berenschot et al. (2021) [81] estimate FLHs for electrolysis at 4500–5000 hours/year when coupled to offshore wind, and 2500–3000 hours/year under a flexible dispatch model. As shown in the boxplot, 50% of Linny-R's experiment results fall between ~4500 and 5225 hours, with an interquartile range of 3500 to 6300. This suggests that most results are broadly in line with the assumptions, though often slightly higher. Outliers—both high and low—are especially visible in Experiment 5. Overall, the Linny-R model aligns with expert estimates while also capturing lower FLH scenarios.

For NH_3 cracking, 50% of FLH values fall between ~5000 and 8000 hours/year. Although specific numbers are limited in the literature, this range supports the understanding that NH_3 crackers are designed for continuous, base-load hydrogen production. Multiple studies [23], [68], [95] confirm that NH_3 crackers are primarily suitable for near-continuous operation, consistent with the model output.

6.3.3 Electricity Shortages

To validate the electricity shortage results in the Linny-R model, Table 6-12 presents the expected shortages from TenneT's 2025 monitoring report [111], while Table 6-13 shows corresponding outputs from the Linny-R model for comparison.

Table 6-12: Expected shortages in the Netherlands in TenneT's 2025 monitoring report [111]

Jaar	Loss of Load Expectation [Uur per jaar]	Expected Energy Not Served [GWh per jaar]
2030	1,1	0,8
2033	12,6	14,1
2035	9,2	15,7

Table 6-13: Validation – Expected shortages in Linny-R Model

Scenario	LOLE (hrs/year)	EENS (GWhe/year)
Base Case	116	74
Best Match - Experiment 3:	15	8
• Low Electricity/Hydrogen Demand • 5.5 GWe Grid Supply Capacity • 7.4 GWe Wind Capacity • 5 GWe BESS Capacity		

As shown in the tables above and results in Appendix E, both LOLE and EENS in the model are significantly higher in than in national estimates. In the base case, the model outputs a 116 hours/year LOLE and 74 GWhe/year EENS, while TenneT's monitoring outlook reports just 1.1–12.6 hours/year and 0.8–15.7 GWhe/year for the entire Dutch system over 2030–2035 [111].

Given that the modelled system (electrolysers, HIC, and hinterland), represents ~50% of national demand, expected outcomes would be closer to 0–6 hours/year LOLE and 0.4–8 GWhe/year EENS. In that context, one scenario from Experiment 3 (see Table 6-13) aligns reasonably well with the TenneT estimates. However, the base case results remain unrealistically high, which can be attributed to several factors:

- No BritNed supply capacity is included in the model, limiting cross-border electricity imports. This is done, because it is assumed BritNed plays a key role in cross-border market coupling, but not in local grid capacity (see Section 4.1.1).
- Grid supply capacity is capped at 5 GWe, although there is a gross transport capacity of 10 GWe. This cap is based on a conservative N-1 reliability criterion (see Section 5.2.1), which ensures grid supply.
- The electricity demand from electrolysis, HIC Rotterdam, and the hinterland may be overestimated relative to realistically available supply.

Together, these limitations cause the model to overestimate electricity shortages. However, rather than undermining the model's validity, these results highlight the system's sensitivity of electricity balance under high-demand scenarios in the Port of Rotterdam.

Another important difference is that the model operates only within the DA market and PPA trading. In contrast, TenneT [111] accounts for multiple markets—such as intraday, congestion, and balancing markets (see Section Electricity Market Design)—which use different pricing mechanisms with additional operational incentives. For instance, intraday markets respond more sharply to scarcity, often with higher prices during shortage events.

Since the shortages in the model do not reduce total electricity demand but mainly increase average system costs through additional VoLL penalties, they do not compromise the model's purpose—which is not to predict shortages precisely. Instead, they offer valuable insight into the boundary conditions of electricity supply and demand in the HIC Rotterdam area.

6.3.4 Storages

To validate the storage outputs of the Linny-R model, Figure 6-19 presents an overview of key storage technologies—such as BESS and salt caverns—showing their typical capacity, storage volume, and time in storage [112]. Figure 6-20 then compares these with installed storage capacities and cycle rates from the Linny-R model across all experiment runs.

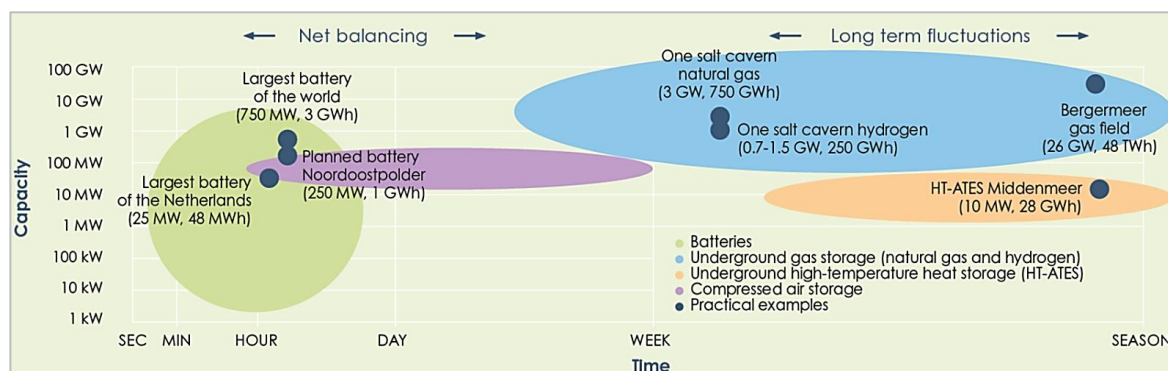


Figure 6-22: Overview of storage technologies by capacity, duration, and examples [112]

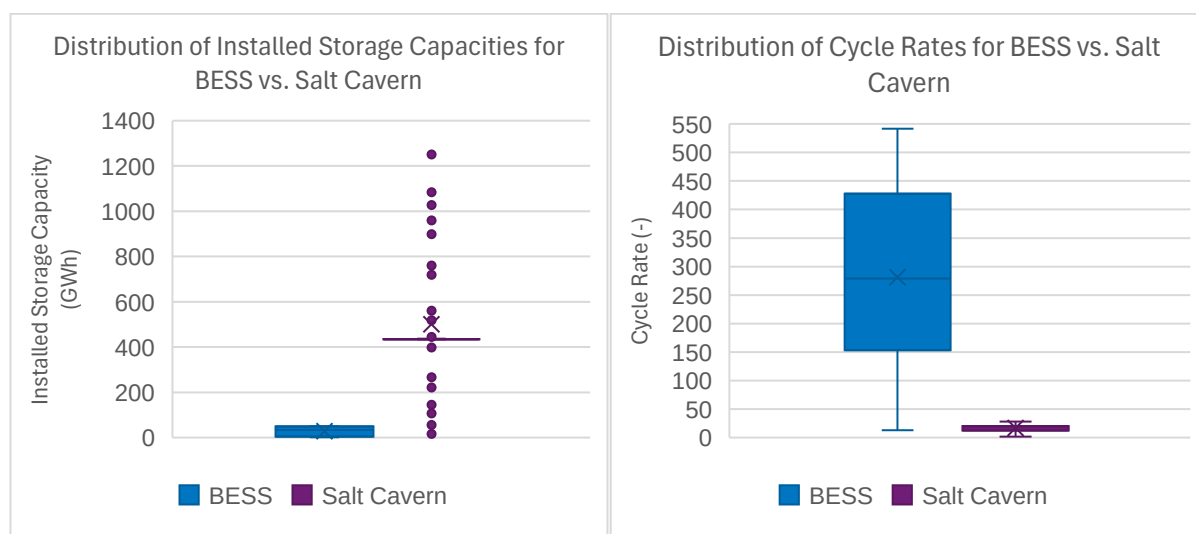


Figure 6-23: Validation – Installed Storage Capacities & Cycle Rates in Linny-R Model

Main observations:

- BESS:
 - In nearly all experiments, BESS storage is optimized to the maximum modelled size (50 GWh_e), indicating it is cost-efficient to scale up storage. As a reference, the largest battery in the world has a capacity of just 3 GWh_e, meaning the modelled system would require at least 16 such batteries to reach this scale.
 - In terms of usage, 50% of BESS cycle rates range between 150–425 cycles per year, with an interquartile range of ~12 to 540. This suggests BESS is charged and discharged every 1–3 days, which matches the expected role of short-duration, high-frequency balancing shown in Figure 6-19. These results support the validity and realistic use of BESS in the model.
- Salt Caverns:
 - Installed storage capacities for salt caverns vary widely across experiments—between 16 and 1250 GWh H₂, with an average of ~500 GWh H₂. As seen in the experiments, salt caverns are more prominent in scenarios with high hydrogen production and limited import availability, where they serve to balance supply and optimize hydrogen flow. The model assumes a typical cavern has a capacity of 250 GWh H₂ (as also illustrated in Figure 6-19), meaning at least 2 caverns are needed on average—and potentially more.
 - Cycle rates are much lower than for BESS: 50% fall between 12.5 and 20 cycles per year, with an interquartile range of ~2 to 30. This implies caverns are fully emptied every 2 to 4 weeks, consistent with their long-duration storage role shown in Figure 6-19. These findings confirm that salt caverns are used realistically and effectively within the model.

6.4 Main Takeaways on Experimentation

The experimentation phase systematically explored the effect of key uncertainties on system performance through a structured set of over 400 model runs. Combining sensitivity (Experiment 1) and scenario-based experiments (Experiments 2–5), this approach enabled both targeted analysis and broad exploration of plausible system configurations. This phase provided the basis for answering SQ1 and SQ2.

Findings show that, under the modelled assumptions, domestic hydrogen production via electrolysis is highly sensitive to electricity costs (PPA price), CAPEX, and hydrogen import prices. These three factors consistently drive cost-competitiveness, particularly in Experiment 2. Meanwhile, grid supply capacity and electricity demand are the dominant influences on system availability and system costs, with BESS providing essential short-term flexibility. The share of hydrogen produced by electrolysis is primarily governed by hydrogen demand and wind electricity availability, while hydrogen imports—when constrained—significantly affect domestic production capacity and storage deployment. Salt cavern hydrogen storage is deployed only in scenarios of domestic hydrogen oversupply (such as Experiment 4), which is realistic because ammonia crackers can be switched on dynamically, meaning long-duration storage is only required when surplus wind electricity produces more hydrogen than can be immediately used or imported hydrogen can be curtailed.

Under volatile market conditions (e.g. 2022), unregulated PPA resale can lead to opportunistic system behaviour and distorted LCOH values, highlighting potential hydrogen policy risks. Furthermore, providing electrolyzers with (additional) DA market access lowers overall system costs but raises LCOH_{electrolysis}.

Cross-experiment analysis shows that robust system performance occurs only within a narrow uncertainty space: just 18% of all scenarios result in cost-competitive electrolysis, and only 25% achieve low energy shortages (LOLE < 20 hours/year). Yet, electrolyzers demonstrate a strong systemic role, with 72% of all scenarios reaching high utilisation levels (>4500 FLH/year). Given that PPAs secure a substantial amount of wind-generated electricity — and therefore installed electrolyser capacity — this suggests that, under favourable conditions, electrolyzers can reliably support both hydrogen supply and overall energy system stability.

Model validation further reinforces the credibility of these results. LCOH_{electrolysis} estimates from Linny-R show close agreement with TNO's RHyCEET tool [27], confirming the reliability of the model's cost breakdown and parameterisation. FLH distributions for electrolysis and NH₃ cracking fall within expected ranges found in literature, demonstrating that operational patterns reflect realistic system behaviour. Storage use and cycle rates align with technological expectations—frequent cycling for BESS and longer-duration balancing for salt caverns. Although the model tends to overestimate electricity shortages compared to TenneT's 2025 monitoring report [111]. This is primarily due to the conservative assumptions on grid capacity and the exclusion of intraday and balancing market mechanisms. As such, the results are not intended to predict absolute shortages, but rather to highlight sensitivity to supply-demand dynamics under varying assumptions.

Overall, the experiments confirm that robust domestic hydrogen supply depends on a careful balance between infrastructure investment, import strategy, and market design. The model's outputs have been validated both quantitatively and structurally, ensuring that the insights derived form a realistic basis for the final analysis and answering of the research questions.

7 Discussion

This chapter synthesises and interprets the results from Chapter 6 in light of the knowledge gap identified in Section 2.4. The findings are set within a broader academic and policy context, focusing on the competitiveness of green hydrogen in the Port of Rotterdam. The discussion reflects on the practical implications of the study, outlines its scientific contributions and assesses its key assumptions and limitations. Finally, it suggests directions for future research that build on this study's insights.

7.1 Interpretation of Results

In line with the research objective, the Linny-R model was developed to explore the conditions under which offshore wind-based (onshore) hydrogen production, could compete with ammonia-based imports in HIC Rotterdam. The core knowledge gap was whether domestic hydrogen production could be cost-competitive and contribute to system reliability, despite the uncertainties in the techno-economic context of HIC Rotterdam. The experiments addressed this by investigating cost thresholds (affordability) and testing system behaviour under varied supply and demand scenarios (flexibility and resilience), all within the boundaries of the assumptions made. The key insights regarding cost-competitiveness, system robustness, and the strategic value of domestic production are presented below.

7.1.1 Cost-Competitiveness Insights

Based on the theoretical framework (see Section Cost Drivers) and prior literature, it was expected that low electricity prices and low electrolyser CAPEX would be the decisive drivers for domestic hydrogen competitiveness. The results partly confirm these expectations: while electricity price and CAPEX level indeed emerge as decisive drivers, the import price exerted a stronger and more dynamic influence than initially anticipated.

Experiment 1 identified these three drivers in the base case and their contribution to the LCOH gap between domestic and imported hydrogen. Experiment 2, which systematically varied them across 75 scenarios, revealed clear breakeven points (see Table 6-7) at which domestic hydrogen ($LCOH_{\text{electrolysis}}$) becomes competitive with imported hydrogen ($LCOH_{\text{import}}$). In practice, this means the interaction between these parameters is crucial: if one is unfavourable, the other two must compensate significantly for cost-competitiveness. However, cost-competitiveness only occurs in 18% of all scenarios (see Section 6.2.6 Cost-Competitiveness) — and two-thirds of these originate from Experiment 2, where all three main drivers are varied. This indicates that the likelihood of domestic hydrogen becoming cost-competitive is low when the three main drivers are not simultaneously favourable.

The electricity price proved the most decisive, even at zero CAPEX, high PPA prices kept the $LCOH_{\text{electrolysis}}$ above €8–10/kg, making domestic production uncompetitive. However, in scenarios where low CAPEX coincided with high import prices, $LCOH_{\text{electrolysis}}$ could tip the balance in favour of domestic hydrogen production, even when PPA prices were high. These tipping points highlight the sensitivity of $LCOH_{\text{electrolysis}}$ to the combination of the three parameters. Furthermore, Experiment 2 revealed a critical dynamic: regardless of the import price, hydrogen imports remain necessary to meet demand, which cannot be fulfilled by domestic production alone. Conversely, when the import price drops below a certain threshold (~€8/kg), the utilisation of the system shifts — electrolyser operation declines while NH_3 cracking increases. This leads to a spike in $LCOH_{\text{electrolysis}}$ and widens the LCOH gap between domestic production and imports. This emphasises that if import prices become too low, operating an electrolyser becomes much less economically attractive, as cheap imported hydrogen will outcompete domestic production.

Given expectations in the literature that hydrogen import prices will decline over time [19], [28], [51], maintaining competitiveness will require sustained reductions in both electricity prices and electrolyser CAPEX. As can be seen in Appendix D, the base case cost values in the model are largely based on current conservative estimates from TNO (2024) [27]. Considering economies of scale and more optimistic future cost projections [3], [19], [28], substantial CAPEX

reductions in practice are plausible, with any remaining gap potentially addressed through subsidies. Electricity prices, by contrast, remain highly unpredictable in the near-future. Assuming PPA prices remain market-aligned, long-term stability could improve through increased system flexibility, potentially driving PPA prices down. This implies that when designing PPAs, decision-makers should account for expected hydrogen import prices and CAPEX trajectories to safeguard future competitiveness. By explicitly incorporating import price as a parameter influencing $\text{LCOH}_{\text{electrolysis}}$, this study extends the conventional techno-economic framework and reinforces earlier literature on the central role of low electricity prices and CAPEX in determining competitiveness.

In Experiment 5, a critical risk emerged: in conditions of extreme price volatility (e.g. in 2022), the model's optimiser used PPAs to resell relatively low-cost electricity instead of producing hydrogen, leading to unrealistically low (even negative) $\text{LCOH}_{\text{electrolysis}}$ values. This mirrors real-world behaviour observed during the 2021–2022 energy crisis, when Dutch horticultural firms profited by reselling their contracted gas instead of consuming it [113], [114]. These cases illustrate how volatile markets can disrupt the intended functioning of contracts.

As long as PPAs allow the resale of electricity, electrolyzers may start acting more like energy traders than hydrogen producers if this proves economically more attractive. In the 2022-simulated scenarios of Experiment 5, the number of FLHs for electrolysis plants fell to ~800–1250, with hydrogen production sacrificed in favour of electricity market profits. In practice, this highlights potential threats to national hydrogen targets set by institutions such as the Port of Rotterdam or the Dutch government. At the same time, the model reflects economically and socially rational behaviour, as it is more efficient for the overall system to resell the electricity rather than use it for hydrogen production under such market conditions. This illustrates that, in such cases, the social optimum is being maximised.

Overall, if import capacity allows, it is not necessarily socio-economically undesirable for PPA electricity to be resold rather than used for hydrogen production, provided that domestic targets are still met. Moreover, this must be interpreted in light of the exceptional market circumstances of 2022, which are unlikely to occur regularly.

7.1.2 System Robustness Insights

System robustness refers to the ability of the electricity and hydrogen system to function effectively under stressful conditions, such as high demand, low wind, import restrictions or fluctuating electricity prices. The most important insights come from Experiment 3, with crucial additional findings from Experiments 4 and 5.

Firstly, constraints on the electricity side determine the reliability results. As shown in Experiment 3 (Figure 6-12 and Figure 6-13), system shortages—measured using LOLE and EENS—are mainly determined by the maximum installed supply capacity of the grid and the demand for electricity. A 20% reduction in maximum installed grid supply capacity leads to an increase in LOLE of more than 400% (Figure 6-2, Experiment 1). By contrast, hydrogen demand has no impact on shortages, due to the model's assumption of unlimited flexible hydrogen imports. This confirms that the robustness of this model is limited not by the availability of hydrogen, but by the ability of the electricity system to meet demand. Only 25% of all scenarios achieve low energy shortages ($\text{LOLE} < 20$ hours/year) (see Section 6.2.6), highlighting the challenge of ensuring high reliability under a wide range of system conditions.

Next, BESS significantly reduces shortages and prevents them especially at when demand is moderate. As shown in Figure 6-12, increasing BESS capacity from 0 to 50 GWhe leads to a significant reduction in LOLE. However, in high-demand scenarios, even maximum BESS capacity (50 GWhe) cannot prevent shortages without sufficient wind and grid capacity. Only scenarios combining high wind capacity, grid capacity of ≥ 5.5 GWe, and BESS capacity of ≥ 50 GWhe BESS achieve a $\text{LOLE} < 10$ hours/year (Experiment 3). This underlines their complementary role: BESS, wind, and grid supply capacity must reinforce each other to ensure robustness.

Additionally, the FLHs of electrolysis fluctuate between ~3800 and 5400 hours/year, depending on the balance between electricity supply and demand (Appendix E.3). Low FLHs occur when electricity is scarce, causing the $\text{LCOH}_{\text{electrolysis}}$ to rise immediately. For example, with only 4 GWe of grid capacity and high demand, FLHs drop to ~3800 and the $\text{LCOH}_{\text{electrolysis}}$ exceeds €12/kg. Despite this sensitivity, electrolyzers demonstrate a strong systemic role: 72% of all scenarios reach high utilisation levels (> 4500 FLH/year) (see Section 6.2.6), underscoring their ability to provide stable

hydrogen output under a majority of conditions. This illustrates the interrelation between robustness and affordability: cost-effective hydrogen production requires a stable system environment.

Furthermore, Experiment 4 highlights the importance of flexible imports. When the capacity of NH₃ cracking plants is limited, the system becomes more dependent on domestic production, increasing the pressure on the electricity grid and the availability of wind electricity (Table 6-8). In these cases, suboptimal electrolysis capacity or insufficient wind energy leads to shortages and the system may resell PPA electricity more often (Table 6-9), reducing hydrogen production in favour of arbitrage on the electricity market. In addition, salt cavern hydrogen storage appears only in scenarios of domestic hydrogen oversupply (as in Experiment 4), which is realistic because crackers can be switched on dynamically—meaning long-duration storage is only needed when surplus wind electricity generates more hydrogen than can be immediately used or when imports can be curtailed. Fixed import restrictions therefore remove an important buffer and exposing the vulnerability of domestic production.

Experiment 5 adds a temporary dimension by subjecting the system to a stress test in a volatile year (2022). Despite sufficient physical capacity, extreme fluctuations in electricity prices cause the optimiser to prioritise the resale of PPA. In some cases, the FLH of electrolysis drops to only 800-1250 hours/year (Table 6-10; Figure 6-15). This is not due to capacity shortages, but because, for the whole system, arbitrage becomes economically more efficient.

Taken together, these findings show that the robustness of the modelled system depends on the following four key conditions: grid capacity ≥ 5.5 GWe; BESS ≥ 35 GWh; stable, predictable electricity prices; and sufficient import capacity. Only when all these conditions are met simultaneously can the system deliver green hydrogen reliably and affordably.

7.1.3 Strategic Value of Domestic Production

In addition to pure costs-competitive and system stability insights, maintaining domestic hydrogen capacity also has intrinsic strategic value. Domestic hydrogen production offers strategic advantages in terms of energy independence and security of supply that imports alone cannot provide. The results show that when import capacity is unlimited and inexpensive, the model consistently opts to import most of the hydrogen due to cost considerations. However, this does not take into account a major risk: dependence on one single source. If domestic hydrogen remains persistently more expensive than imports, decision-makers face a choice between accepting import dominance, supporting domestic capacity for strategic reasons, or a hybrid approach. These options and their trade-offs are discussed in greater detail in Section 7.4.

In experiment 4, where hydrogen import capacity is fixed instead of optimised, the system always compensates for a lower import capacity by installing more electrolysis capacity (if sufficient wind electricity is available). This continues until domestic production completely replaces imports. Although this scenario is not cost-optimal in a free market, it is illustrative: it suggests that domestic hydrogen can act as a kind of insurance. If external supplies are restricted (due to geopolitical problems, supply chain disruptions or price shocks), domestic production and storage ensure that industries in the port are not suddenly left without crucial hydrogen. In principle, this currently also applies to strategic natural gas reserves, and after Russia turned off the gas tap in 2022, this even led to a 90% filling obligation for European gas reserves for the winter [115].

The Port of Rotterdam and the Netherlands have policy objectives for their own hydrogen ecosystem (e.g. 4 GWe of electrolysis capacity by 2030 [2]), partly to avoid excessive dependence on imports. It is important to emphasize that achieving these targets will likely require protective measures (such as import quotas or domestic hydrogen requirements) or significant cost reductions (in electricity and CAPEX) to close the gap, ensuring that domestic hydrogen is also used when imports are possible. In addition, domestic production has advantages for industrial development: it enables local value creation (jobs, technological development) and may give the port a competitive advantage in terms of knowledge and innovation. If HIC Rotterdam develops expertise in balancing a hybrid hydrogen system (production + imports), this know-how could be a strategic asset as the hydrogen economy grows in Europe and the rest of the world.

7.2 Academic Contribution

This study makes four important contributions to academic literature:

- Firstly, it fills the knowledge gap identified in Section 2.4 by providing a location-specific techno-economic comparison of domestic hydrogen production and imports, adapted to the particular context of HIC Rotterdam.
- Secondly, the thesis expands the conventional techno-economic framework by explicitly modelling hydrogen import prices and its dynamic impact on system behaviour and LCOH_{electrolysis} results. By treating hydrogen imports as a flexible and cost-sensitive system component, the analysis provides new insights into tipping points and cost drivers for competitiveness, extending previous static evaluations [19], [27], [28], [51], [98].
- Thirdly, the study highlights the strategic system value of maintaining domestic hydrogen production capacity – beyond pure cost-effectiveness considerations. Scenario experiments demonstrate how domestic production can serve as a buffer against limited imports, thereby contributing to system resilience and energy independence. This dimension is often overlooked in techno-economic studies. By linking technical modelling results to broader policy issues such as security of supply and system governance, this research bridges the gap between technical analysis and strategic policy debate.
- Fourthly, the study applies and integrates established methodological frameworks into the design and execution of the scenario experiments. This provides a template for future research on complex interconnected electricity and hydrogen systems in areas such as HIC Rotterdam:
 - Modelling and Simulation Life Cycle [75] to structure model design, validation, and iterative refinement.
 - Exploratory Modelling and Analysis (EMA) [76] to explore uncertainty through large ensembles of scenarios (e.g. Experiments 2–5).
 - XLRM framework [78] to map exogenous uncertainties (X), policy levers (L), relationships (R), and performance metrics (M) in the modelled system.
 - The 4 A's [79] to assess outcomes in terms of availability, affordability, acceptability, and accessibility.

Furthermore, the Linny-R model developed and used in this study offers a solid basis for further research. As discussed in Section 7.5, there are still many areas that can be explored.

7.3 Limitations

While this study offers valuable insights into the dynamics of the hydrogen system in HIC Rotterdam, a number of limitations must be considered when interpreting the results. These limitations can be divided into three categories: model assumptions, data limitations and policy scope.

Model Assumptions

- The model assumes given prices, wind series, and perfect prior knowledge, without considering behavioural responses or adaptive investment decisions. This approach excludes feedback loops between demand, supply, and market dynamics. For instance, the model assumes fixed historical interactions, based largely on 2024 data (except in Experiment 5), between variables like the hourly wind capacity factor and DA prices. As a result, volatility and path dependency may be underestimated, and these interactions could differ significantly in a future energy system, particularly with a higher share of renewable energy sources and more flexible demand. This could mean that both volatility and the frequency of extreme price events are underestimated, potentially skewing competitiveness and robustness results.
- Technical aspects such as ramping behaviour, start-up times and minimum loads are not taken into account. Similarly, self-discharge and capacity loss in BESS, as well as cracking losses during ammonia input, are modelled in a simplified manner. This could lead to an overestimation of operational flexibility and an

underestimation of system losses, leading to overly optimistic estimates of both system reliability and hydrogen affordability.

- The assumption of a single node ('copper plate'): The HIC area in Rotterdam is modelled as a single unlimited node for electricity and hydrogen flows, without spatial congestion or internal bottlenecks. This simplification ignores possible transmission constraints within the port, which in reality could limit both electricity supply to electrolyzers and the distribution of domestic/imported hydrogen. As a result, the model may overestimate the feasibility of meeting demand under stressed conditions.
- Electricity and hydrogen demand must always be met in the model. As a result, the utilisation of both domestic production and imports may be overestimated, as shortages can only occur if it is physically impossible to supply more hydrogen, which can mask more subtle reliability risks.
- In Experiments 1, 2, 3, and half of 5, hydrogen imports are assumed to be unlimited. This effectively removes import availability as a limiting factor, potentially overstating system reliability and underestimating the strategic value of domestic production capacity in constrained import scenarios.
- The model minimises total system costs rather than the utility or profit of individual actors. This system-optimised perspective does not capture strategic bidding behaviour, contractual obligations, or asymmetric incentives. For instance, the resale of PPAs is treated purely from a system-cost standpoint, which could diverge significantly from actual trader decisions and lead to misaligned predictions about electrolyser operation in volatile markets.
- Important components have been excluded to keep the model focused and simple. These choices reduce the complexity of the model but limit the completeness of the representation of the broader electricity and hydrogen system landscape. These exclusions include:
 - Onshore wind electricity and solar electricity (aggregated in grid supply),
 - Hydrogen-fired electricity generation,
 - Offshore electrolysis,
 - Alternative hydrogen carriers (e.g. LOHC, LH₂),
 - Small-scale or above-ground hydrogen storage.

Data Limitations

- The model presents a stylised scenario for 2030 and beyond. Rather than predicting the behaviour of the system, it examines its sensitivity under selected assumptions. Important parameters, such as hydrogen demand, wind profiles and price dynamics, are based on fixed scenario inputs rather than probabilistic uncertainty distributions. This limits the range of possible futures explored and could understate the impact of extreme or unexpected development
- The model runs on an hourly basis over a single simulation year, capturing seasonal patterns but omitting long-term dynamics, such as investment cycles or multi-year paybacks. It assumes perfect foresight within the year, reducing realism under uncertainty. Electricity DA prices from 2024 (and 2022 in one experiment) are used as proxies, though future prices remain uncertain due to increasing renewables, electrification, and grid constraints.
- The intraday market, congestion markets, and balancing markets are not modelled. In addition, load has been converted to an hourly resolution (instead of a quarter of an hour), which smooths short-term variability. In reality, this finer-scale variability could increase the need for flexibility measures such as BESS, leading to higher operational costs than modelled.
- Electricity and hydrogen demand is distributed across HIC Rotterdam area and its hinterland, but is not broken down further by sector (e.g. transport, industry, built environment). This choice prioritises flows system-level flows, but reduces connectivity and the ability to evaluate sector-specific flexibility or transition pathways.
- The model only includes onshore electrolysis and imports based on ammonia. Although this is in line with the short-term policy focus and technical maturity, it does not consider potentially promising alternatives in the medium to long term.

- The model includes only onshore electrolysis and ammonia-based imports, aligning with short-term policy priorities and technical maturity. However, this omits other potentially cost-competitive pathways (e.g., offshore electrolysis, LOHC, LH2), potentially biasing the evaluation against solutions that could become viable.
- Hydrogen flows are evaluated using LCOH, but the model does not simulate market-clearing mechanisms, bidding strategies, or endogenous price formation. This limits the realism of competitiveness assessments, especially in a future with liberalised hydrogen markets where market power, bidding behaviour, and volatility could materially shift utilisation patterns.

Policy Scope

- Variable tariffs for the high-voltage grid are represented in stylised form, while broader time-of-use or dynamic pricing structures are excluded. Grid and market participation costs are also simplified, ignoring the potential influence of regulatory adjustments, subsidy mechanisms (e.g. SDE++) or CO2 floor prices. This simplification may understate the effect of future tariff reforms or incentives on hydrogen competitiveness.
- The model assumes that current regulatory structures remain stable over time, excluding the possibility of policy changes that could significantly alter system design or cost structures — such as carbon taxation reforms, mandatory hydrogen blending (such as the refinery route [60]), or revised grid prioritisation rules. If such policies are introduced, the competitiveness landscape for domestic versus imported hydrogen could shift substantially. Notably, recent policy development as the Nieuw Klimaatpakket en Voorjaarsnota 2025 [61] are not included in this study.
- All investment decisions are optimised simultaneously within a single year, without accounting for phased project development, financing constraints, or policy implementation. This instant build-out assumption risks overestimating the pace at which capacity can be deployed, particularly for large-scale infrastructure projects with long permitting and construction timelines, such as the national hydrogen backbone [47].

While the Linny-R model provides a systematic and transparent framework for exploring system-level trade-offs, the outcomes presented in this study describe an idealised system configuration. In practice, real-world inefficiencies, unexpected market behaviour, and various uncertainties may cause actual results to diverge from the modelled outcomes. The findings should therefore be seen as indicative patterns and potential developments rather than precise forecasts. Nevertheless, by isolating and systematically varying uncertainties under controlled assumptions, the model offers clear insight into the relative importance of different exogenous factors and policy levers — insights that remain relevant even if exact quantitative values differ in practice.

7.4 Practical Implications

This section translates the model’s findings into concrete implications for three stakeholder groups: the Port of Rotterdam Authority, industrial hydrogen users and producers, and national and EU policymakers. It indicates what each group needs to consider in light of the results of this study, thereby addresses the final sub-question (SQ3).

7.4.1 For the Port of Rotterdam Authority

As system coordinator and infrastructure developer, the Port of Rotterdam Authority (PoR) must navigate the balance between economic efficiency and strategic resilience. The model indicates that, even with abundant offshore wind potential, at least 5.5 GWe of grid supply capacity and 35 GWhe of BESS are essential for maintaining a stable electricity-hydrogen system. These thresholds are technically feasible but require significant, timely infrastructure investments—projects that are often subject to long permitting processes, stakeholder negotiations, and cost uncertainties.

From a purely market perspective, low-cost hydrogen imports frequently outcompete domestic production. While the PoR also benefits economically from import activity through terminal operations, trade volumes, and associated services, its strategic considerations extend beyond domestic costs alone. Excessive dependence on imports could expose the port

to geopolitical risks, supply disruptions, or unfavourable market shifts. Maintaining a minimum level of domestic hydrogen capacity—whether continuously operated or kept in reserve—could therefore serve as a form of ‘strategic buffer’.

The results also highlight a contractual risk: without production obligations or resale restrictions in PPAs, volatile electricity markets may incentivise electrolyser operators to prioritise electricity arbitrage over hydrogen production. While this behaviour can be economically rational in the short term, it undermines hydrogen supply reliability, potentially conflicting with PoR’s strategic objectives.

7.4.2 For the Industry

The hydrogen industry in HIC Rotterdam involves both providers (electrolyser operators and import terminal operators) and hydrogen consumers (companies in the chemical industry, the refining sector and heavy transport). The study offers various implications for both sides of the hydrogen market.

For domestic providers, the model shows that cost-competitiveness with imports is mainly sensitive to three interdependent factors—PPA electricity price, electrolyser CAPEX, and hydrogen import price. The break-even combinations identified are narrow and in many cases will not be met without policy intervention on electricity pricing and capital cost reduction, or without favourable market shifts in import prices. Even if CAPEX declines in line with optimistic projections, electricity prices remain a crucial factor. Given the current uncertainty about the business case of offshore wind capacity in the North Sea [116], significant decreases in PPA prices are unlikely without financial support mechanisms. The results also suggest that domestic providers may face strategic trade-offs between operational flexibility and long-term offtake certainty: reselling electricity during high-price periods can be profitable in the short term but risks eroding customer trust and undermining the stability of the hydrogen supply system.

For import providers, the model shows that their competitiveness increases significantly when global import prices are low or logistics chains operate without disruption. However, in such cases, domestic production is quickly sidelined, potentially leading to long-term market dominance by imports in HIC Rotterdam. While this may be commercially beneficial for import terminal operators, it also raises questions about the resilience of the overall system and the risk of over-dependence on external suppliers.

For consumers, the findings indicate that off takers must make a strategic well-balanced choice between spot markets/imports and long-term contracts with domestic producers. The study shows that excessive dependence on imports makes companies vulnerable in crisis scenarios. Overreliance on imports can increase exposure to supply and price volatility, particularly during crisis scenarios such as those seen in 2022. Although not explicitly tested in this model, flexible consumers—those able to shift demand in time—are better positioned to cope with variability in wind electricity and can contribute to system stability. However, in practice, achieving such flexibility may require costly process adjustments, contractual arrangements, and advance planning to align operational schedules with market conditions.

7.4.3 For Policymakers

From a policy perspective, the conditions under which domestic production becomes competitive are relatively stringent. Without a balanced occurrence of low PPA electricity prices, reduced CAPEX, and moderately high import prices, cost-competitive domestic production is unlikely in a free market setting. This raises the question of whether competitiveness should be the sole policy target, or whether domestic production should also be maintained for its strategic value—such as energy autonomy, system resilience, and industrial capacity building.

The study shows that a robust energy system, such as that of HIC Rotterdam, must be understood within the interconnected context of electricity and hydrogen availability, system flexibility, and market design. Policies that target only a single element—such as subsidising electrolysis—are unlikely to deliver both competitiveness and resilience. In addition, the development of a hybrid system of imports plus domestic production for HIC Rotterdam could serve as a transferable ‘blueprint’ for other European ports, but only if its enabling conditions are realistically achievable given infrastructure timelines, market volatility, and political commitment.

7.5 Future Research Directions

This study identifies several avenues for advancing the understanding of hydrogen system dynamics in the Port of Rotterdam. The proposed directions fall into four main themes: market behaviour, spatial constraints, contractual design, and model refinement.

Market Behaviour

In future research, agent-based modelling could be used to investigate how individual actors—such as electricity suppliers, hydrogen producers, consumers, and traders—respond to uncertainty, price signals, and policy incentives within an interconnected energy system such as HIC Rotterdam. This would provide a deeper understanding of market outcomes, going beyond merely optimising system costs.

Network Constraints within HIC Rotterdam

This study assumes a single-node system (“copper plate principle”) and does not consider internal bottlenecks in the network, such as congestion. A spatially explicit model could assess the impact of location-specific constraints on the deployment of electrolysis, network reliability, and investment needs in the HIC Rotterdam area.

Contractual Designs

Experiment 5 revealed unintended incentives under volatile electricity prices. Future research could assess the effectiveness of alternative PPA designs, such as minimum production clauses or resale restrictions, in ensuring a hydrogen supply while maintaining investment returns and system robustness.

Model Refinement

Several structural refinements could improve realism and extend applicability:

- **Data realism:** Use multiple representative weather years and corresponding electricity price profiles to capture interannual variability.
- **Technology learning:** Incorporate learning curves for key CAPEX components (electrolysers, storage) to reflect cost reductions with scale.
- **Network representation:** Replace the copper plate assumption with a multi-node setup to model congestion and local capacity constraints.
- **Market representation:** Endogenously determine hydrogen prices via a market-clearing mechanism, include merit-order electricity dispatch, and model competing hydrogen pathways (grey, blue, LOHC, LH2).
- **Import variability:** Include seasonal and multi-year variation in import capacity and price to evaluate resilience under different dependency levels.

By addressing these themes, future research can move from stylised cost–reliability trade-offs toward a more comprehensive, actor-aware, and spatially realistic understanding of interconnected energy systems—strengthening both academic insight and policy relevance.

8 Conclusion and Recommendations

This study investigated the conditions under which domestic green hydrogen production in the Harbour Industrial Cluster (HIC) Rotterdam could be competitive with hydrogen imports. The study compared onshore electrolysis, based on offshore wind electricity, with ammonia-based imports, assessing the most important technological and economic uncertainties and system configurations. A series of over 400 future scenarios were simulated using Exploratory Modelling and Analysis (EMA) with the assistance of Linny-R modelling to test the impact of uncertainties such as energy prices, demand profiles, electrolysis' CAPEX, and tariffs on the electricity and hydrogen system, thereby aiming to provide an answer to the main research question:

“Under which techno-economic and strategic conditions is onshore hydrogen production, powered by offshore wind, cost-competitive with ammonia-based hydrogen imports, while contributing to a robust hydrogen and electricity system in the Port of Rotterdam?”

8.1 Summary of Key Findings

8.1.1 Answer to the Sub-Questions

This chapter summarises the findings of the three sub-questions and explains how the various model-based experiments and scenario analyses led to the answers. The first two sub-questions relate to the techno-economic conditions and system configurations, while the third sub-question draws strategic conclusions for HIC Rotterdam's main stakeholders. Each sub-question is addressed in sequence.

***SQ1:** “Which techno-economic factors most significantly affect the cost-competitiveness of onshore hydrogen production, powered by offshore wind, relative to ammonia-based hydrogen imports in the Port of Rotterdam?”*

This study shows that cost-competitiveness depends highly on three interdependent factors: the electricity price under power purchase agreements (PPAs), electrolyser investment costs, and the price of imported hydrogen. Of these, the PPA price is the most decisive—low electricity costs are essential for achieving a levelised cost of domestic hydrogen that can compete with imports. The results also reveal clear break-even thresholds: only specific combinations of low PPA prices, reduced investment costs, and import price levels allow domestic production to match or undercut imports. If one factor becomes unfavourable, the other two must improve substantially to preserve competitiveness. These findings highlight the need for a coordinated strategy that aligns investment support, electricity pricing structures, and import market dynamics to secure a viable long-term role for domestic green hydrogen in the Port of Rotterdam.

***SQ2:** “Under which system combinations—of electricity and hydrogen supply, demand, and storage—does onshore hydrogen production, powered by offshore wind, provide a stable and cost-effective contribution to the electricity and hydrogen system in the Port of Rotterdam?”*

This study shows that, in the modelled system, electricity availability and flexibility—determined by demand, wind generation, grid capacity, and storage—are the primary stress factors, while hydrogen demand plays a secondary role due to import flexibility. Salt cavern hydrogen storage contributes to stability only when domestic hydrogen production exceeds immediate demand, such as during periods of surplus wind power or when imports can be curtailed.

The results show that stable and cost-effective integration of domestic hydrogen production into the energy system can only be achieved with configurations that combine sufficient grid supply capacity and large-scale electricity storage. Across a wide range of conditions, electrolyzers demonstrate a strong systemic role, operating at full load for a large number of hours and thereby delivering stable hydrogen output under most of the circumstances.

When imports are restricted or market conditions are volatile, domestic production becomes more vulnerable to system constraints, and electrolyzers may switch from hydrogen production to electricity arbitrage—undermining supply stability. Ensuring a robust contribution from electrolysis therefore requires coordinated investment in high-voltage grid infrastructure, storage capacity, and market incentives that prioritise hydrogen production under changing conditions.

SQ3: “What are the strategic implications—of the electricity and hydrogen—system conditions under which onshore hydrogen production, powered by offshore wind, plays a stable and cost-competitive role for stakeholders in the Port of Rotterdam?”

The strategic role of domestic hydrogen production in the Port of Rotterdam depends not only on cost-competitiveness, but also on its ability to enhance system robustness and energy autonomy under uncertain future conditions. In order to maintain stable and affordable green hydrogen supply, four enabling conditions are identified: sufficient high-voltage grid supply capacity, sufficient storage capacity, predictable electricity prices, and flexible hydrogen imports. Without these conditions being met, electrolyzers risk being underutilised or repurposed as electricity traders, which would undermine both hydrogen supply and climate goals. Therefore, stakeholders must view domestic hydrogen production as a strategic buffer that supports system resilience, energy security, and long-term industrial competitiveness, even if it is not always the cheapest option.

8.1.2 Answer to the Main Research Question

This study shows that onshore hydrogen production powered by offshore wind electricity can be competitive with ammonia-based imports in the Port of Rotterdam, but only under specific techno-economic and strategic conditions. The model findings indicate that cost-competitiveness of domestic production depends highly on a balance between favourable power purchase agreement (PPA) prices for electricity, reduced investment costs, and the level of import prices. The interaction between these factors is critical: if one becomes unfavourable, the other two must compensate substantially to maintain competitiveness.

Beyond economic viability of electrolyzers, a stable energy system depends heavily on adequate high-voltage supply capacity and large-scale electricity storage to prevent costly shortages. In addition, salt cavern hydrogen storage contributes to stability only in cases of domestic hydrogen oversupply, when surplus wind electricity generates more hydrogen than can be immediately used or imports can be curtailed. However, the ability of the interconnected hydrogen and electricity system to maintain robust is complicated by exogenous factors such as volatile electricity markets and import constraints, which highlights the need for stabilising policy instruments—such as well-designed PPAs—that provide price certainty for both offshore wind producers and electrolyzers, while safeguarding the role of domestic hydrogen production.

Ultimately, domestic hydrogen production offers economic and strategic value, providing a buffer against external shocks and contributing to energy security, system resilience and industrial autonomy in the HIC Rotterdam area and the Netherlands.

8.2 Strategic Recommendations

This study shows that domestic hydrogen production in the Port of Rotterdam can only be competitive and strategically valuable if favourable market conditions, sufficient infrastructure, and supportive policies are in place. Achieving this in practice will require coordinated action from all stakeholders. The recommendations below translate these findings into targeted actions for the Port of Rotterdam Authority, industry, and policymakers.

8.2.1 For the Port of Rotterdam Authority

Maintain minimum domestic hydrogen capacity

Ensure the preservation of a baseline level of electrolysis capacity—such as 2.5 GWe by 2030—even in periods when imported hydrogen is more cost-competitive. This will safeguard energy security in the event of potential geopolitical

disruptions, market volatility, or supply chain disruptions. In cases of domestic hydrogen oversupply, salt cavern hydrogen storage can help balance production and demand on a biweekly level.

Accelerate investment in critical infrastructure

Prioritise the timely expansion of high-voltage grid supply capacity towards at least 5.5 GWe and the deployment of approximately 35 GWhe of electricity storage, as indicated by the model results. While these thresholds are derived from stylised scenarios and should be interpreted with caution, they provide a useful benchmark for avoiding production curtailment, maintaining system stability, and enabling cost-effective integration of domestic hydrogen production. These investments should be closely coordinated with TenneT, relevant distribution system operators, and market parties involved in large-scale electricity storage to ensure technical feasibility, optimise system integration, and align investment timelines.

8.2.2 For the Industry

Develop cost-competitiveness strategies across interdependent variables

Domestic hydrogen producers should coordinate efforts to reduce electrolyser CAPEX, advocate for lower PPA electricity prices, and closely monitor import price dynamics. Competitiveness is only achieved through specific combinations of these three variables, and improvements in one must offset unfavourable conditions in the others. By aligning investment decisions with market trends and technology cost curves, producers can increase the likelihood of achieving break-even with imports across a wider range of scenarios.

Manage operational flexibility without compromising offtake stability

Domestic hydrogen producers should balance the economic benefits of electricity resale during high-price periods with the need to maintain stable hydrogen offtake agreements. While occasional arbitrage can improve short-term profitability, excessive reliance on this practice risks undermining customer trust and reducing system stability. Hybrid contractual models that combine PPAs with flexible but reliable offtake arrangements can provide a workable compromise between operational agility and long-term supply commitments.

Build resilience into import operations

Import terminal operators should diversify their supply chains and prepare contingency plans for low-probability, high-impact events such as geopolitical disruptions or extreme price shocks. Although low import prices strengthen their cost-competitiveness, overreliance on a limited set of suppliers increases systemic vulnerability. Diversification strategies and strategic inventory holding would enhance the port's capacity to maintain supply under stressed conditions and contribute to overall system resilience.

Align consumer contracting strategies with system stability

Hydrogen consumers—particularly in energy-intensive sectors—should balance spot market purchasing with long-term domestic supply contracts. While reliance on imports can provide short-term cost advantages, it exposes companies to significant volatility during crisis scenarios. By securing part of their supply from domestic producers under stable contractual terms, consumers can safeguard production processes and contribute to system-level stability.

8.2.3 For Policymakers

Balance cost-competitiveness with strategic value in policy design

National and EU policy should recognise both the economic and strategic roles of domestic hydrogen production. Even when imports are cheaper, maintaining domestic capacity supports energy security, industrial development, and supply resilience. To close the cost gap with grey hydrogen and imports, instruments such as SDE++ and the EU Innovation Fund could be expanded through higher feed-in tariffs, Contracts for Difference, or direct capital subsidies [26], [84]. Directives such as RED III/IV should also be regularly updated to embed the strategic value of green hydrogen within a stable, long-term framework.

Adopt an integrated system context

Policy interventions should consider the electricity–hydrogen system as a whole. The model demonstrates that factors such as energy availability, system flexibility, and market design are highly interconnected, meaning that measures must be coordinated rather than targeting a single aspect—such as subsidies for electrolysis—in isolation. Competitiveness and resilience cannot be achieved by focusing on one parameter alone; a holistic approach that integrates market design reforms with physical capacity investments will deliver more robust and enduring outcomes.

Use HIC Rotterdam as a blueprint for interconnected energy systems

Policymakers should position the Port of Rotterdam as a demonstration case for integrating domestic production and imports into a resilient hybrid energy system. The enabling conditions identified in this study could inform the development of similar systems in other European ports, promoting knowledge transfer and coordinated policy design. Demonstration projects—such as Shell’s Holland Hydrogen I electrolyser [63]—combined with active stakeholder engagement will be essential to ensure the blueprint is both transferable and credible.

9 Reflection

This chapter concludes the thesis with a reflection on the research process. The reflection is organized into three key sections: the process (which includes the topic and method, the modelling phase, and my experience working with the Port of Rotterdam), my experience working with Linny-R, and a personal reflection on the overall research experience.

9.1 Reflection on the Process

Overall, I am satisfied with both the process and the final outcome of my thesis. Before I started the process, I had three main preferences: I wanted the topic to be related to the energy transition, I wanted to conduct a modelling study, and I wanted to collaborate with a company (preferably in Rotterdam). Fortunately, all three of these wishes came true, which provided a solid foundation for the process.

9.1.1 Topic and Method

Once I secured the opportunity to collaborate with the Port of Rotterdam, the next step was to identify a research topic that aligned with both the Port's activities and the objectives of the CoSEM programme. Through a series of discussions, it became clear that the integration of offshore wind electricity and hydrogen production via electrolysis in HIC Rotterdam would be a relevant and timely research topic. This approach aligns with both Dutch and Port of Rotterdam policies, as the Port is well-suited for landing large amounts of offshore wind electricity. However, a key challenge identified was that the cost of domestically produced hydrogen is currently not competitive with imports from regions with cheaper renewable energy sources. As such, this became the focus of my thesis.

At the beginning, the topic was somewhat undefined, which presented both an opportunity and a challenge. While the flexibility allowed exploration, it also meant that the scope was initially uncertain. As I delved deeper, I recognized the complexity and interconnectedness of electricity and hydrogen systems. These systems were not only technologically complex but also shaped by economic and policy factors, making the research a typical CoSEM problem at the intersection of technology, economics, and policy.

Initially, I had intended to incorporate a wide range of technical, economic, and policy factors into the model. However, as the research progressed, I found that it was impractical to model policy directly due to its evolving nature. Instead, policy's influence could be captured indirectly through adjustments to techno-economic parameters, such as cost assumptions and production scenarios. This shift in approach helped refine the focus of my research, allowing me to create a more manageable and effective model.

In addition, I initially set a relatively high number of KPIs (9 in total) to measure performance, which allowed me to capture a broad set of results across the four A's of evaluation. While this provided a comprehensive view, focusing on fewer KPIs would have enabled a deeper, more targeted analysis. Refining the KPIs would have simplified the model results and improved the clarity and relevance of the findings, offering a more focused assessment of the key factors influencing hydrogen production and its cost-competitiveness.

Regarding the methodology, I am satisfied with my decision to use a modelling framework. The structured approach provided by the modelling and simulation lifecycle was invaluable, guiding me through each stage of the process. It also enabled me to generate quantitative insights, which were crucial in assessing the techno-economic feasibility of hydrogen production, providing a solid basis for decision-making. Ultimately, the methodology helped me gain a deeper understanding of the dynamics involved in integrating offshore wind electricity with large-scale hydrogen production.

9.1.2 Modelling Phase

The modelling phase was the most challenging aspect of my thesis, and I encountered frequent struggles throughout the process. Constantly making decisions about the scope and assumptions was difficult, particularly due to my perfectionist tendencies. One of the first lessons I learned in modelling is that it's impossible to model the entire world. However, my desire to create a comprehensive and impressive model made simplification more difficult than anticipated.

For instance, I decided to focus on domestic hydrogen production via electrolysis and imports in the form of ammonia, while intentionally leaving out other production methods such as grey or blue hydrogen and alternative import routes. This was a significant assumption that I revisited and questioned regularly during the research process.

Another challenge arose during the interpretation phase, where I struggled to maintain a healthy distance from the model. I often found myself getting caught up in “model language” and had to constantly remind myself that the model was a tool to support the thesis, not the thesis itself. This realization helped me stay focused on the broader research objectives and prevented me from becoming overly fixated on the model’s details.

9.1.3 Working with Port of Rotterdam

My experience working with the Port of Rotterdam was very positive. It was valuable to have access to in-house expertise and refreshing to alternate between meetings with my university and Port of Rotterdam supervisors, offering a balance of academic and practical perspectives.

One of the highlights of my time with the Port was the opportunity to visit both the office and operational areas, including a boat tour through the harbour and a visit to the Enecogen gas plant. These experiences gave me a much deeper understanding of the Port’s operations and its critical role in the energy transition. They provided invaluable real-world context that significantly enriched my thesis experience.

The office environment itself was another aspect I truly appreciated. The positive and collaborative atmosphere made the work experience much more enjoyable and contributed greatly to how I experienced my time there. It reinforced my belief in the value of a supportive workplace culture.

At times, I did feel somewhat like an external consultant, working independently on my own project rather than as part of a team with shared deliverables. This experience taught me that I thrive in a team-oriented environment, and I prefer working collaboratively with others. This is something I will carry forward in my career, as I have learned how crucial teamwork is in driving successful outcomes. Nevertheless, the guidance I received from my Port colleagues was constructive, and I had many insightful discussions that expanded my understanding of the topic.

Finally, working with the Port of Rotterdam allowed me to gain a deeper insight into the organization’s structure and its importance. I learned about the various departments, their interactions, and the essential role the Port plays—not only in the harbour area but also in the broader context of the Netherlands’ economy and energy transition. This understanding enhanced my experience and further solidified my appreciation for the Port’s impact on both the national and global scale.

9.2 Reflection on Working with Linny-R

Looking back, using Linny-R was the right decision, though a challenging one. The tool offers endless possibilities, which, while beneficial, also introduce a wide array of choices. Its ability to integrate and visualise various data and outcomes was especially useful for discussing the model with experts, as I could clearly explain my modelling choices per cluster. However, as I became more familiar with Linny-R, I realized that such model flexibility requires a structured approach. While the tool offers many features, I found that keeping the model focused on its core objectives was essential to avoid unintended results. Several times, I made changes to the model that ultimately led to complications, which underscored the importance of maintaining a clear and structured approach throughout the process.

One of the significant challenges I faced was the model’s long run times. For example, in Experiment 2, which involved 75 scenarios, the computation time was about three hours, with each run taking approximately two minutes. This made the experimentation phase particularly time-consuming, and on several occasions, I discovered minor errors in my experiments. These errors required me to re-run the model, often wasting several hours. A significant contributing factor to the long run times was the limited computing power of my laptop, which considerably extended the overall processing time. As a result, I often found myself leaving the model running overnight just to have results ready the next morning, which, while necessary, was both time-consuming and frustrating.

Another challenge was the lack of a complete manual. While Linny-R is not particularly difficult to use, I hadn’t worked with it in four years, and I was not fully familiar with the latest version. Had I known there was no complete manual, I might have considered using other tools. Fortunately, the developer (Pieter Bots) was always very quick to respond to

my questions and provided valuable guidance throughout the process, which was crucial for keeping the research on track.

Once a manual is available, Linny-R will become even more user-friendly. A comprehensive guide will save time and reduce the need for contacting Pieter for basic queries. The manual should also address the tool's computational limitations, helping users avoid setting up overly large experiments and understand the feasible limits. I also struggled at first with determining how large my experiments could be, and a more detailed manual would have clarified this more quickly.

In addition to this, I identified areas for improvement in Linny-R, particularly in terms of data visualization. While I used Excel to visualize my results, it would be more efficient if Linny-R allowed users to directly select and visualize data within the tool itself. Features such as boxplots or 3D surface plots would provide more intuitive ways to interpret and present results, streamlining the analysis process and making the software more versatile.

9.3 Personal Reflection

Looking back on the past six months, I feel proud of what I have accomplished. It has truly been a rollercoaster—marked by periods of significant progress followed by setbacks when I got stuck in modelling issues. Despite these ups and downs, I maintained a 'growth' mindset and stayed motivated, always striving to keep a clear overview of the process. One of the key factors in staying organized was having a complete outline of my thesis, which was linked to the different steps of the modelling lifecycle. This was particularly helpful, as the iterative nature of the modelling cycle often meant revisiting previous steps. Having a structured overview allowed me to organize my work into distinct sections and ensured I moved through the various phases of the research.

I also realized that I work best under time pressure. While I am generally calm and organized, I found that my perfectionism often led to stress, especially when it came to making decisions. I struggled with the feeling that there might always be a better option, which made it difficult to make choices, particularly about the scope of the research or specific modelling decisions. In hindsight, I recognize that, especially in a six-month project, it's crucial to limit the scope to something manageable. Deadlines ultimately helped me make these decisions more decisively, and in the future, I hope to embrace this approach earlier in the process.

Lastly, this thesis deepened my understanding of the complexity and dynamics of the energy transition. Throughout the research, new reports and developments emerged, and I found myself tempted to incorporate them all. However, I learned to resist the urge, focusing on the task at hand. The constant evolution of the field is precisely what fascinates me, and it has further strengthened my desire to pursue a career in energy transition. I look forward to applying the broad CoSEM perspectives I've gained to real-world challenges in this area.

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Appendices

A. Literature Review

1. Search Strategy

For this thesis' proposal, the literature search is conducted in the scientific Scopus database in February 2025, with search terms covering all core concepts. To ensure broader applicability, HIC Rotterdam is replaced by a general focus on (industrial) ports. In addition, several synonyms are included to increase completeness. The final search query in Scopus was:

"(TITLE-ABS-KEY (electrolysis OR electrolyser OR hydrogen OR H2 OR "green hydrogen" OR "renewable hydrogen" OR "hydrogen carrier" OR ammonia OR "liquid organic hydrogen carrier" OR lohc OR methanol OR "synthetic natural gas" OR sng) AND TITLE-ABS-KEY (import OR (offshore AND wind) OR "wind to hydrogen" OR "wind-to-hydrogen" OR "power to hydrogen" OR "power-to-hydrogen" OR "power-to-x" OR "power to x") AND TITLE-ABS-KEY (system OR hub OR "supply chain" OR "value chain" OR infrastructure OR network OR corridor OR cluster OR valley OR ecosystem) AND TITLE-ABS-KEY (port OR harbor OR harbour OR seaport OR "maritime port" OR "industrial port" AND NOT (airport OR "air port")))"

This resulted in 45 scientific articles.

2. Selection Process

The final selection of 45 scientific articles was based on the following criteria:

- Date: Only articles published after 2019 were included to ensure relevance and avoid outdated findings.
- Type of paper: Only peer-reviewed, accessible journal articles were considered to maintain high-quality validated research.
- Relevance and applicability: Articles focusing exclusively on niche topics such as Liquefied Natural Gas (LNG), Onshore Power Supply (OPS) or planning were excluded if they did not address the integration of offshore wind electricity for green hydrogen production or the broader hydrogen import system.

The figure below provides a visual overview of the selection process using the PRISMA flow diagram [117].

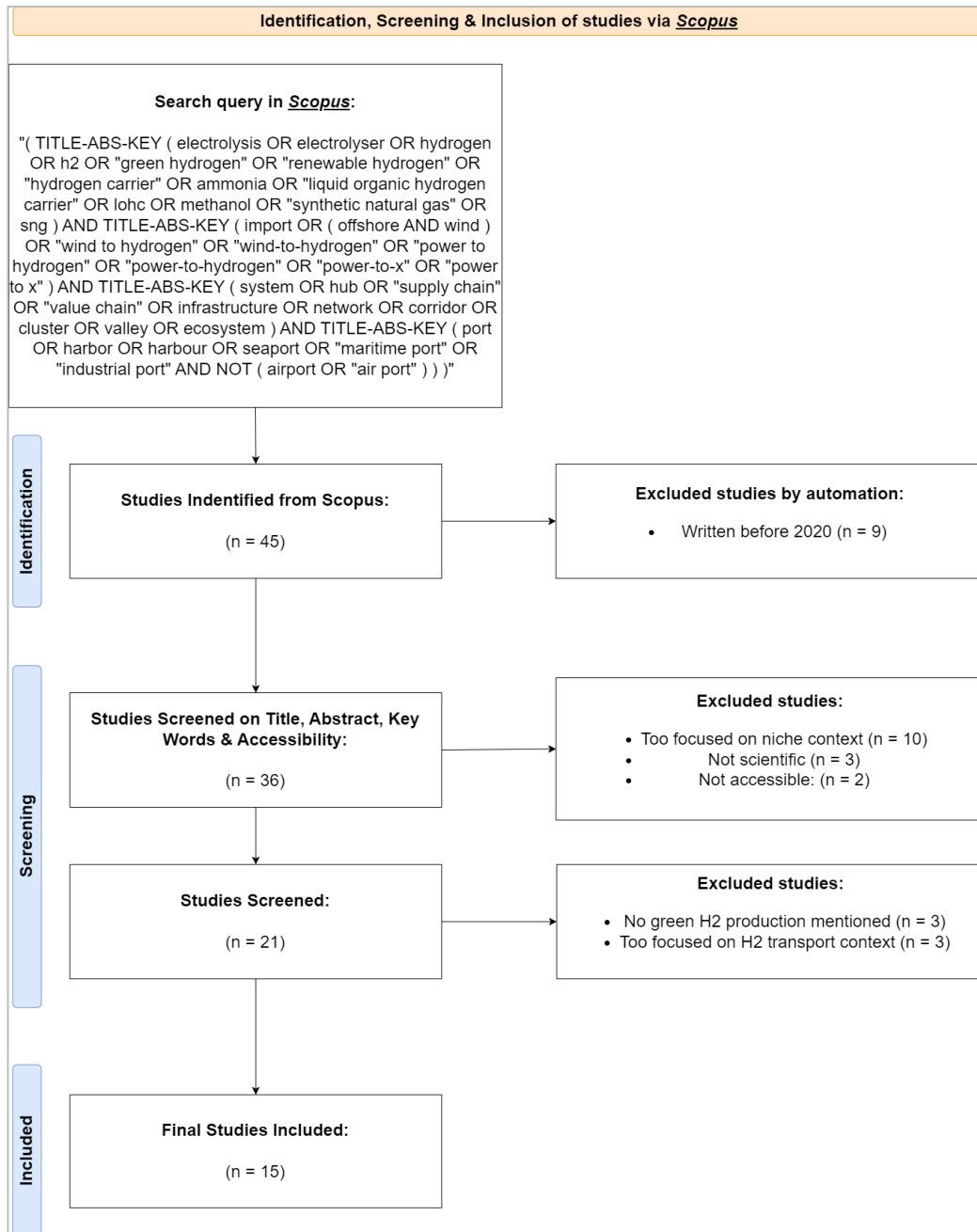


Figure X-1: Search Query & PRISMA Flow Diagram

3. Selected Literature

The tables below presents the final selection of scientific articles, and public reports used for the literature review.

Table X-1: Selected Scientific Literature

Reference	Title
[118]	Alternatives for Transport, Storage in Port and Bunkering Systems for Offshore Energy to Green Hydrogen
[119]	Opportunities and Challenges of Hydrogen Ports: An Empirical Study in Australia and Japan
[120]	Multi-port coordination: Unlocking flexibility and hydrogen opportunities in green energy networks
[72]	Economic Scheduling of Integrated Port Energy System Considering the Flexible Operating Condition of Hydrogen Equipments
[66]	Techno-economic assessment of far-offshore hydrogen-carrying energy vectors off the Iberian Peninsula
[64]	Techno-economic analysis of hydrogen production from offshore wind: The case of Brazil
[65]	A geospatial method for estimating the levelized cost of hydrogen production from offshore wind
[71]	A multi-objective planning tool for the optimal supply of green hydrogen for an industrial port area decarbonization
[121]	Hydrogen corridors in Europe: strategies and countries involved
[70]	Optimal decarbonization strategies for an industrial port area by using hydrogen as energy carrier
[68]	The economics of global green ammonia trade – “Shipping Australian wind and sunshine to Germany”
[67]	Techno-economic evaluation of two hydrogen supply options to southern Germany: On-site production and import from Portugal
[73]	Energy systems integration and sector coupling in future ports: A qualitative study of Norwegian ports
[122]	A review on ports’ readiness to facilitate international hydrogen trade
[69]	The role of hydrogen as enabler of industrial port area decarbonization

Table X-2: Selected Grey Literature

Reference	Title
[1]	The Paris Agreement
[3]	Global Hydrogen Review 2024
[5]	REPowerEU
[123]	Northwest European Hydrogen Monitor 2024
[2]	Klimaatakkoord
[57]	Routekaart Waterstof
[4]	Nationaal Plan Energiesysteem [NPE]
[58]	Programma Energiehoofdstructuur [PEH]
[8]	Programma Noordzee 2022 – 2027 - VAWOZ 2030
[6]	North Sea Energy Outlook [NEO]
[9]	Eindrapport voorverkenning VAWOZ 2031-2040
[10]	Programma Verbindingen Aanlanding Wind Op Zee (VAWOZ) 2031-2040
[46]	Het energiesysteem van de toekomst: de II3050-scenario's
[48]	Systeemintegratie wind op zee: Fase A pVAWOZ 2031-2040
[74]	Routekaart NPVI: Van grijs naar groen.
[48]	Elektrolyzers, nettarieven en het elektriciteitssysteem
[28]	Groene waterstof: de praktische uitdagingen tussen droom en werkelijkheid
[19]	Productie, import, transport en opslag van waterstof in Nederland.
[124]	Infrastructure Outlook 2050
[125]	Havenbedrijf Rotterdam Klimaatdoelen 2030
[62]	In drie stappen naar een duurzaam Industriecluster Rotterdam-Moerdijk 2050
[11]	Cluster Energie Strategie Industriecluster Rotterdam-Moerdijk
[23]	Executive summary of pre-feasibility study by fluor for: Large-scale industrial ammonia cracking plant

4. Synthesis of Literature

Table X-3: Number of citations, geographical focus and the occurrence (by scale) of concepts in the selected scientific literature

Reference	Number of Citations	Geographic Focus	Production & Technology			Techno-Economics			Policy, Regulation & Risk		Infrastructure & Integration			
			Green H2 production	Offshore wind electricity	H2 storage & distribution	Techno-economic analysis	Optimal H2 supply mix	(future) scenarios analysis	Policy interventions & regulations	Risk management & safety	H2 import	Port decarbonization	Integrated energy systems	Sector coupling
[118]	5	-	3	1	2	1			1	1	1	1		1
[119]	3	Australia & Japan	3			1			1	1	1	1		1
[120]	1	-	3	1		1			1	1		1	1	
[72]	4	China	3	1		1			1	1		1	2	1
[66]	13	Iberian Peninsula	3	2		3	1	1	1	1	1			
[64]	0	Brazil	3	2		2			1	1		1		
[65]	31	Ireland	3	3		3	1	1	1					
[71]	3	Singapore	2		1	2	1	1	1	1	1	2		1
[121]	0	Europe	2			1			3	1	1			
[70]	14	-	3			2	2	1	1	1		2		1
[68]	57	Australia - Germany	2	1		3	1	1	2	1	1	1		
[67]	18	Portugal - Germany	3			2			1	1	1			
[73]	0	Norway	2	1		1	1	1	1	1	1	3	1	3
[122]	51	Worldwide	3			1		1	3	1		1		
[69]	31	Europe	3			1			1	1		3		1
Occurrence			41	13	2	25	7	7	20	14	8	17	4	9
			56			39			34		48			

Table X-4: Geographic scope, summary and (numerical) insights of the selected 'Grey' literature

Reference	Title	Level	Summary	(Numerical) Insights
Global and European Context				
[1]	The Paris Agreement	World	Global climate agreement setting emissions reduction targets to limit global warming	- Aim for max. 1.5°C global warming compared to pre-industrial levels (pre-1750); - Net-zero CO₂ target by 2050
[3]	Global Hydrogen Review 2024	World	Provides a global overview of hydrogen production, policies, and market developments	- Global hydrogen demand: ~100 Mt in 2024, 2.5% increase compared to 97 Mt in 2023; - Electrolyser installed capacity: 5.2 GW in 2024, 9x growth compared to 0.6 GW in 2021
[5]	REPowerEU	European Union	A European strategy to reduce dependency on Russian fossil fuels and accelerate renewable energy adoption, including hydrogen	Target EU: 10 Mt of domestic renewable hydrogen production + 10 Mt of imports by 2030
[123]	Northwest European Hydrogen Monitor 2024	Northwest Europe	Analyses hydrogen demand, supply, and infrastructure development in NW Europe	- EU hydrogen demand: ~7.5 Mt in 2024 (NW Europe: 4.5 Mt), EU aims for 20 Mt renewable hydrogen demand by 2030; - NW Europe aims for 30-40 GW installed electrolyser capacity by 2030
Dutch Context				
[2]	Klimaatakkoord	The Netherlands	Dutch national climate agreement outlining sectoral measures for emissions reduction	CO₂ reduction target: -49% (2030); -95% (2050) compared to 1990 levels
[57]	Routekaart Waterstof	The Netherlands	Outlines the Dutch strategy for hydrogen development, focusing on production, import, infrastructure, and integration	- Dutch hydrogen production goal: 6-8 GW installed electrolyser capacity by 2030; - Total hydrogen import NL: ~360-600 PJ by 2030, ~15x growth compared to 24-36 PJ in 2025
[4]	Nationaal Plan Energiesysteem [NPE]	The Netherlands	Strategic vision for the Dutch energy system, covering hydrogen, renewables, and infrastructure	- Dutch 2020-2050 vision for energy end-use sectors: Carbons' role declines sharply, replaced by greener alternatives; Electricity and hydrogen rises significantly, with hydrogen taking over carbon's role; and Heat demand increases slightly.; - By 2040: 15-20 GW installed electrolyser capacity; - By 2050: 70 GW installed offshore wind capacity & 3.5-5 GW installed nuclear power capacity
[58]	Programma Energiehoofdstructuur [PEH]	The Netherlands	Focuses on energy infrastructure development, including hydrogen networks and offshore wind connections	Different energy infrastructure scenarios towards 2050 including expansion of the high-voltage grid and pipelines, development of power plants, large-scale electrolysis, and underground energy storage
[8]	Programma Noordzee 2022 – 2027 - VAWOZ 2030	The Netherlands	Framework for North Sea spatial planning, emphasizing offshore wind and hydrogen infrastructure	By 2050 offshore wind electricity has 38-72 GW installed capacity, which means 170-325 TWh energy output and 1.5-3 GW/year growth rate
[6]	North Sea Energy Outlook [NEO]	The Netherlands	Examines offshore wind potential, grid integration, and future energy scenarios in the North Sea	There are several technical options for the integrations of Nort Sea energy production, with hydrogen and electricity playing important roles
[9]	Eindrapport voorverkenning VAWOZ 2031-2040	The Netherlands	A preliminary study on offshore wind landing options and grid connections	By 2031, 7.4 GW of offshore wind capacity is planned to be brought ashore at Maasvlakte, Rotterdam
[10]	Programma Aanlanding Wind Verbindingen Op Zee (VAWOZ) 2031-2040	The Netherlands	Plans for offshore wind power integration into the Dutch energy system between 2031-2040	- Dutch offshore wind installed capacity is planned to increase significantly, reaching 21 GW by 2033, 50 GW by 2040 and 70 GW by 2050. - The VAWOZ program plans to land 29 GW of energy as electricity and hydrogen between 2031 and 2040, using 10 electricity cables (2 GW each) and 1-2 hydrogen connections

[46]	Het energiesysteem van de toekomst: de II3050-scenario's	The Netherlands	Provides a scenario analysis for the Dutch energy system transition	Dutch grid operators have developed 4 scenarios for the 2050 energy system: Decentralized Initiatives (DEC), National Leadership (NAT), European Integration (EUR), and International Trade (INT)
[48]	Systeemintegratie wind op zee: Fase A pVAWOZ 2031-2040	The Netherlands	Study on system integration challenges of large-scale offshore wind electricity	- Six scenarios are modelled for 2040, based on II3050 [46] with two additions: Industrial Decline and Transit to Foreign Markets - All scenarios assume 50 GW offshore wind by 2040, in line with VAWOZ targets
[74]	Routekaart NPVI: Van grijs naar groen.	The Dutch Industry	Provides a roadmap for the Dutch industrial decarbonization, emphasizing hydrogen adoption	Dutch policy targets green electricity (2030): - Onshore wind & solar: 35 TWh/year - Offshore wind: 21 GW capacity (80+ TWh/year) (Routekaart Wind op Zee) - Electricity is crucial to achieving the EU RED target of 40% renewables (Fit for 55) 70% of total electricity will come from renewable sources Dutch policy targets renewable & low-carbon hydrogen: - Electrolysis capacity: 3-4 GW by 2030 (Klimaatakkoord), 8 GW by 2032 - EU target: 40 GW electrolysis capacity by 2030 (Fit for 55) Industrial hydrogen use: 42% renewable hydrogen by 2030, 60% by 2035 (RED III)
[48]	Elektrolyzers, nettarieven en het elektriciteitssysteem	The Netherlands	Analyses the impact of electrolysis on electricity grid tariffs and system flexibility	- By 2030, grid costs for hydrogen production under standard grid access are ~€2/kg, contributing to a total cost of €6.5–12/kg. - With flexible grid access, costs could drop to €1/kg, allowing electrolyzers to connect despite grid congestion
[28]	Groene waterstof: de praktische uitdagingen tussen droom en werkelijkheid	The Netherlands	Study on the practical challenges of green hydrogen implementation	- A climate-neutral energy system by 2050 requires phasing out grey hydrogen and scaling up green hydrogen use - The transition depends on sufficient market demand, which remains highly uncertain in the long term - The development of green hydrogen production and import chains is hindered by multiple bottlenecks
[19]	Productie, import, transport en opslag van waterstof in Nederland.	The Netherlands	Analysis of hydrogen value chains in the Netherlands.	Production costs hydrogen: - Green: 6.3-9.1 €/kg H2 in 2030 & 5.6-8 €/kg H2 in 2040 - Blue: 1.8-3.5 €/kg H2 in 2030 & 1.9-3.6 €/kg H2 in 2040 - Grey: 1.9-3.2 €/kg H2 in 2030 & 2.2-3.6 €/kg H2 in 2040 Import costs green hydrogen via ammonia: - Ship: 7.3-7.9 €/kg H2 in 2030 & 5.3-5.6 €/kg H2 in 2040 - Pipe: 4.1-7.3 €/kg H2 in 2030 & 3.5-5.3 €/kg H2 in 2040
[124]	Infrastructure Outlook 2050	The Netherlands	Long-term vision for energy infrastructure development	All the scenarios show that not only the electricity, but also the existing gas transport infrastructure in the Netherlands will play a crucial role in the future energy systems
Port of Rotterdam Context				
[125]	Havenbedrijf Klimaatdoelen 2030	Rotterdam Port of Rotterdam	Describes the Port of Rotterdam's sustainability goals for 2030, including hydrogen and emissions reduction	CO₂ reduction targets by 2030 compared to 1990 levels: - Scope 1: Achieve 90-100% reduction - Scope 2: Achieve 50% reduction Scope 3: Achieve 20-80% reduction
[62]	In drie stappen naar een duurzaam Industriecluster Rotterdam-Moerdijk 2050	HIC Rotterdam	Outlines steps for decarbonizing the Rotterdam-Moerdijk industrial cluster by 2050	The Rotterdam-Moerdijk industrial cluster generates €13 bln in added value and employs 75,000 people. It processes 2,000+ PJ of energy annually, consuming 260 PJ, mainly from refinery byproduct gases and natural gas. In 2016, emissions totalled 18.6 MT CO ₂
[11]	Cluster Energie Strategie Industriecluster Rotterdam-Moerdijk	HIC Rotterdam	Outlines the energy strategy for the Rotterdam-Moerdijk industrial cluster, including hydrogen	To drive the transition, a strategy is being developed based on four pillars: Infrastructure

				• Renewable energy & hydrogen • Circular production • Sustainable transport
				Goals 2030:
[63]	Port of Rotterdam developing Europe's Hydrogen Hub	HIC Rotterdam	Outlines the Port of Rotterdam's hydrogen strategy, emphasizing a mix of domestic production and imported hydrogen	• 2.5 GW (= 0.25 Mt H₂) electrolysis capacity • 0.6 Mt of local production (0.25 Mt green H₂, 0.35 Mt blue H₂) • Setting up 8 more import terminals for ammonia, LOHCs or liquid hydrogen • 4 Mt of green hydrogen & derivatives import (= 40% of EU ambition)
[23]	Executive summary of pre-feasibility study by fluor for: Large-scale industrial ammonia cracking plant	HIC Rotterdam	Assesses the feasibility of an ammonia cracking facility to support hydrogen imports in Rotterdam	The study investigates a central ammonia cracking facility in the Port of Rotterdam, capable of producing 1 Mt of hydrogen annually (~3,000 tons/day or 1.3 MNm ³ /h H ₂), requiring 20,000 tons of ammonia daily

B. Overview of Potential Offshore Wind Landfall Sites

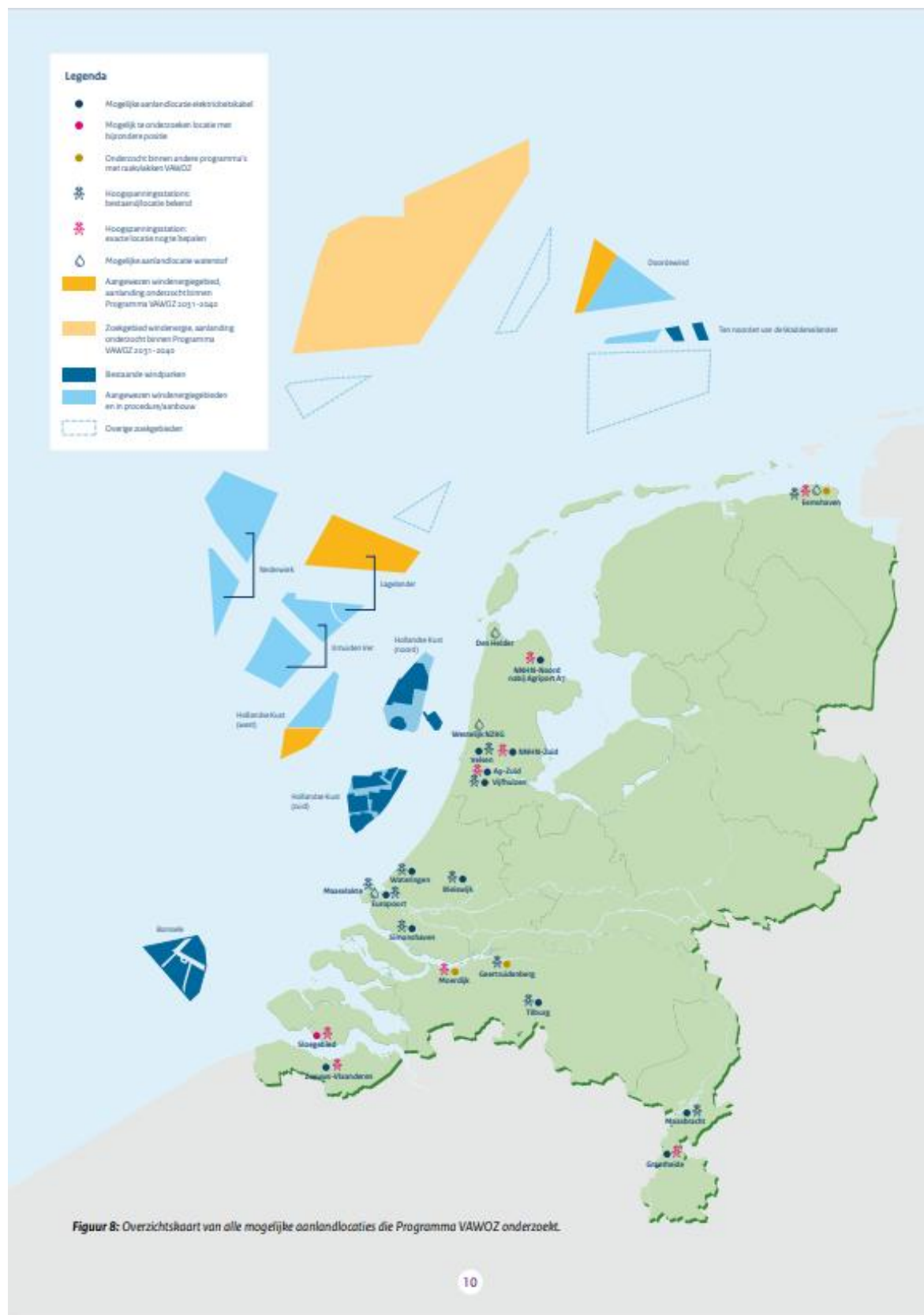


Figure X-2: Overview of all potential offshore wind landfall sites (VAWOZ 2031-2040) [10]

C. Comprehensive XLRM Framework

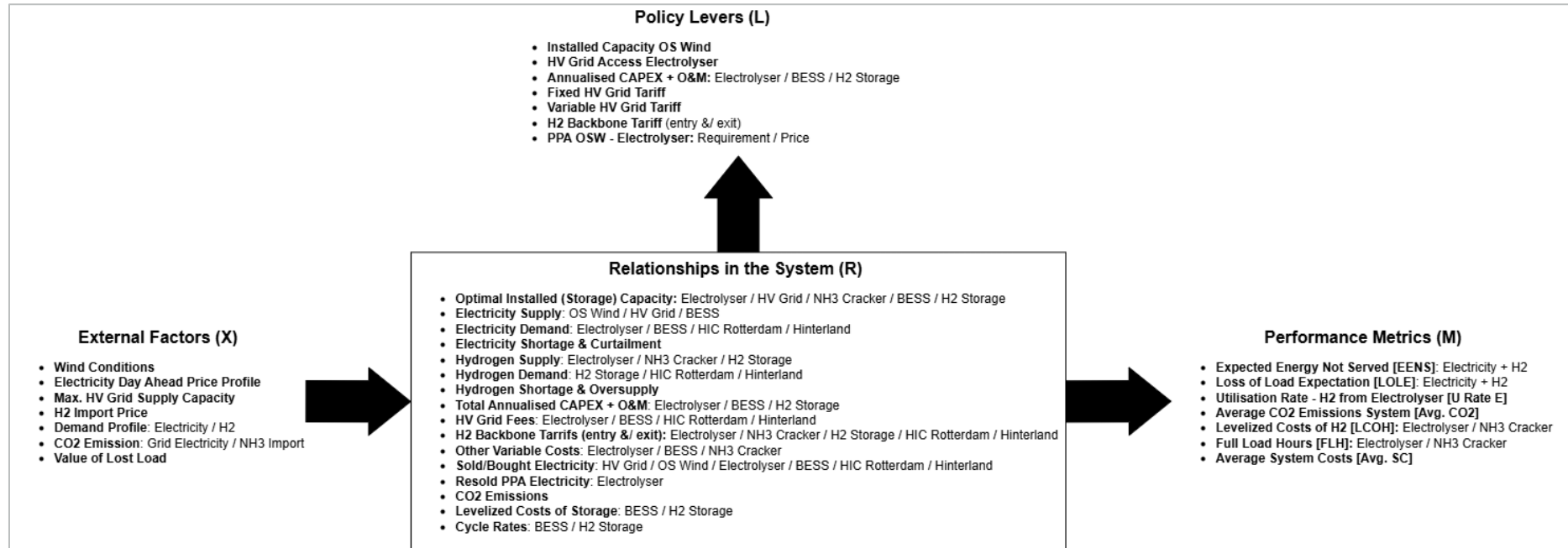


Figure X-3: Comprehensive XLRM of the Research

D. Model Data

1. Static and Scenario-Dependent Parameters

Table X-5: Non-Financial Parameters

Parameter	Static Base Value	Scenario Values	Unit	Note	Reference
Electricity System					
Max. Installed Grid Supply Capacity	5	4, 4.5, 5, 5.5, 6	GWe	Based on 10 GWe HV grid capacity (4 * 2.5 circuits) combined with N-1 safety constraint	Own assumption based on CE Delft and DNV [48], [56], [86]
CO2 Emission - Grid Electricity	35		tonnes CO2/GWe	Average of estimations: 70 in 2030, and 0 in 2050	[83]
OSW Installed Capacity	7.4	7.4, 13.4, 19.4	GWe	Future projections for 2030, 2040 and 2050 are included as scenario values	[9], [25], [56]
OSW Capacity Factor	Dynamic		Factor (0-1) of OSW installed capacity		[87]
Max. Installed Storage Capacity BESS	5	5, 20, 35, 50	GWe	Based on a portion ($\sim 1/5$) of Dutch future projections of flexible resources	[29], [56]
Charge/Discharge Capacity BESS	1.25	1.25, 5, 8.75, 12.5	GWe	Based on 4-hours system (e.g. 1 GWe/ 4 GWe)	[56], [85]
Round Trip Efficiency BESS	95		%		[29]
Electricity Demand - HIC Rotterdam	Dynamic	Low; Mid; Peak	GWe/hour	Future projections are included as scenario values; 70% of maximum load between 21-7u	[11], [56]
Electricity Demand - Hinterland	Dynamic	Low; Peak	GWe/hour	Based on a portion ($\sim 1/6$, $\sim 1/4$) of Dutch load	[88]
Hydrogen System					
Installed Capacity Electrolyser	Optimised		GW H2	Optimised	Own assumption
Electricity Efficiency Electrolyser	0.7021		GWh H2/GWe		[27]
HV Grid Access Electrolyser	0	0, 50	% of OSW installed capacity	Allowed under REDIII if grid consists of at least 90% renewable electricity	Own assumption
Max. Installed Capacity NH ₃ Cracker	Optimised	0, 1, 2, 3, 4, 5, 6, 7, 8, Unlimited	GW H2	Optimised	Own assumption
CO2 Emission - Imported H2	16.955		tonnes CO2/GWh H2	NH ₃ supply CO2 emissions, according to REDIII	[51]
Installed Storage Capacity per Salt Cavern	250		GWh H2/salt cavern	1 salt cavern	[38]
Store Capacity per Salt Cavern	1.8		GWh H2/salt cavern		Own assumption based on injection rate [38]
Destore Capacity per Salt Cavern	3.6		GWh H2/salt cavern		Own assumption based on extraction rate [38]
Round Trip Efficiency Salt Cavern	0.98		%		[37]
H2 Demand - HIC Rotterdam	15	15, 30, 45, 60	TWh H2/year	Future projections are included as scenario values	[11]
H2 Demand - Hinterland	1.1053		Factor of H2 demand HIC Rotterdam	Connected Deep Green scenario	[126]

Table X-6: Financial Parameters

Parameter	Static Base Value	Scenario Values	Unit	Note	Reference
Electricity System					
Annualised CAPEX + O&M BESS	27		M€/GWe/year		Own calculation (see Table X-7)
Annualised CAPEX BESS Connection	1.65		M€/GWe/year		[85]
Feed-in Tariff Electricity	2.6		€/MWh		[127]
Electricity Tax	1.3		€/MWh		[27]
DA price	Dynamic		€/MWh		[88]
PPA price	80	40; 80 ; 120	€/MWh		Own calculation based on average DA prices [88]
PPA requirement	50	0; 50	% of OSW Electricity Generation		Own assumption based on interview [110]
PPA resellability	100		% of PPA Electricity		Own assumption
fixed HV Grid Tariff	55		M€/GWe/year	Contracted HV GWe per year	[100], [105]
fixed HV Grid Tariff Electrolyser	55	27.5; 55; 82.5	M€/GWe/year		[100], [105]
variable HV Grid Factor	Dynamic		factor (0-1)		[100], [105]
variable HV Grid Tariff	18		€/MWhe	Monthly Max. HV MWhe converted to be hourly -> based on average variable HV grid factor (76%) & 4800 FLH	Own assumption based on Monthly Max. HV MWhe [100]
variable HV Grid Electrolyser	18	9; 18 ; 27	€/MWhe		“
VoLL Electricity	85	-	M€/GWhe		[89]
Hydrogen System					
Annualised CAPEX + O&M Electrolysis	433	25%; 50%; 75%; 100%	M€/GWe/year		Own calculation (see Table X-7)
Annualised CAPEX + O&M Salt Cavern	0.029		M€/GW H2/year		Own calculation (see Table X-7)
Costs: Production H2 -> Conversion to NH ₃ -> Storage NH ₃ -> Shipping NH ₃	0.1957	50%; 75%; 100% ; 125%; 150%	M€/GWh H2	Depreciation included; corresponds to 3.85, 5.78, 7.70 9.63; 11.56 €/kg	[19]
Costs: NH ₃ Storage + Reconversion to H2	0.0224		M€/GWh H2	Depreciation included	[19]
H2 Backbone Entry/Exit Fee	33.09		M€/GW H2	The same H2 Backbone Fee has to be paid by both suppliers and consumers	[27], [97]
VoLL Hydrogen	85		M€/GWh H2	VoLL Hydrogen assumed to be the same as Electricity	Own assumption

Table X-7: Annualised CAPEX + O&M calculation parameters

Parameter	Value	Unit	Note	Reference
BESS				
Economic Lifetime	15	Years		[85]
WACC	8	%		[85]
Corporate Income Tax rate (CITr)	25.8	%		[101]
CAPEX	224.4	M€/GWe		[85]
Annualised CAPEX	21.2	M€/GWe/year		Own calculation (see Section 5.4.2)
Fixed OPEX	5.6	M€/GWe/year	2.5% of CAPEX	[85]
Electrolysis				
Economic Lifetime	15	Years		[27]
WACC	9.5	%		[27]
Corporate Income Tax rate (CITr)	25.8	%		[101]
CAPEX	3353	M€/GWe		[27]
Annualised CAPEX	350.6	M€/GWe/year		Own calculation (see Section 5.4.2)
Fixed OPEX	82.8	M€/GWe/year	2.5% of CAPEX	[27]
H2 Storage in Salt Cavern				
Economic Lifetime	30	Years		[38]
WACC	8	%		[38]
Corporate Income Tax rate (CITr)	25.8	%		[101]
CAPEX	0.27	MEUR/GW H2	Onshore & Short cycle application	[38]
Annualised CAPEX	0.021	MEUR/GW H2/year		Own calculation (see Section 5.4.2)
Fixed OPEX	0.008	MEUR/GW H2/year	2.5% of CAPEX	[37]

2. Dynamic Parameters

Weather Years

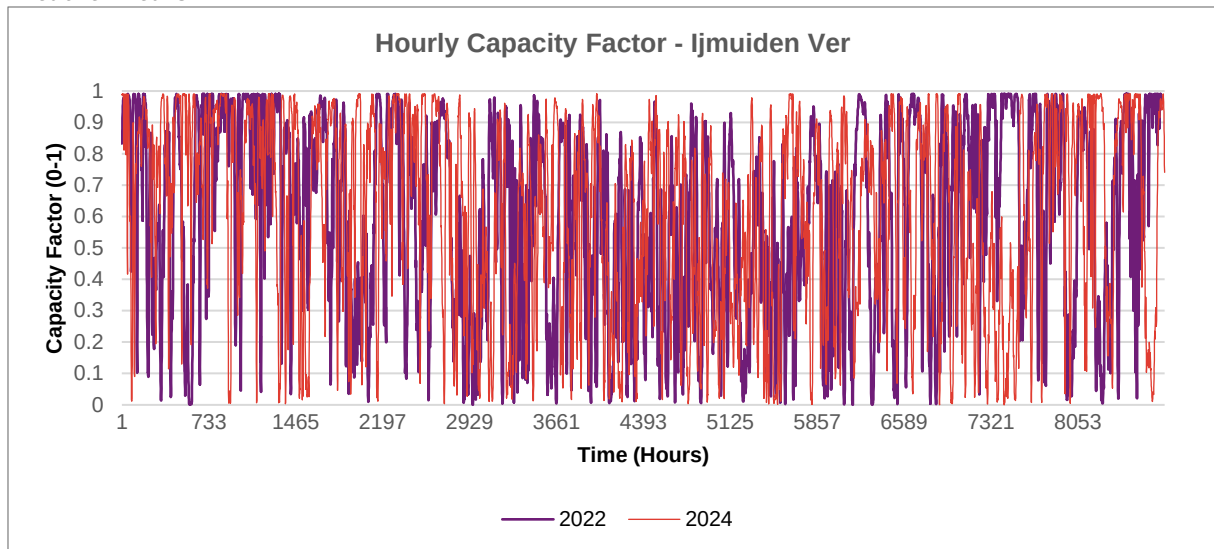


Figure X-4: Hourly Capacity Factor - Ijmuiden Ver in 2022 & 2024

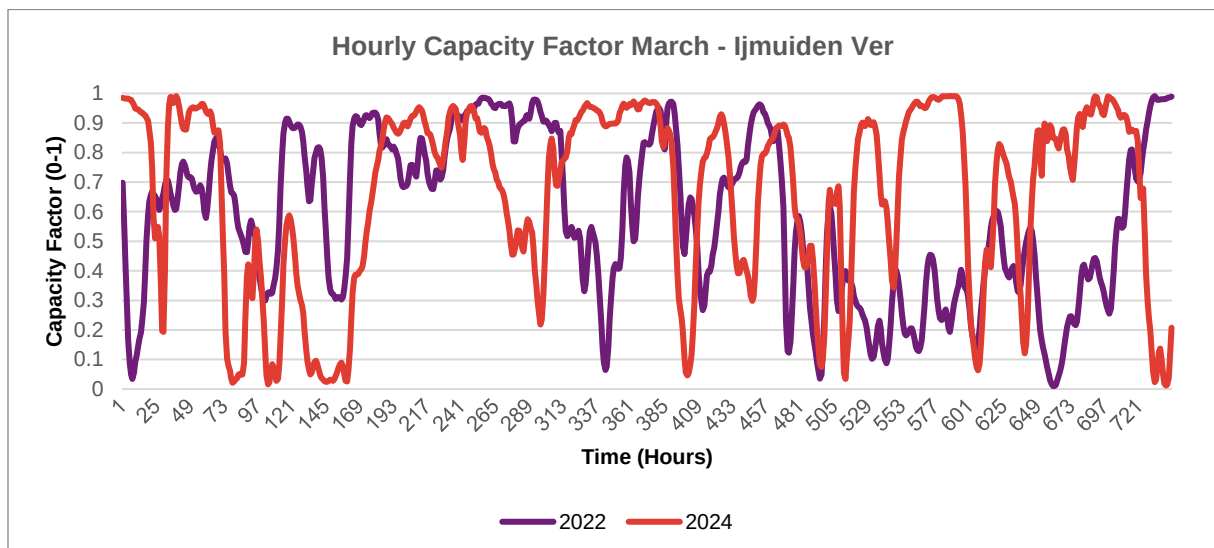


Figure X-5: Hourly Capacity Factor March - Ijmuiden Ver in 2022 & 2024

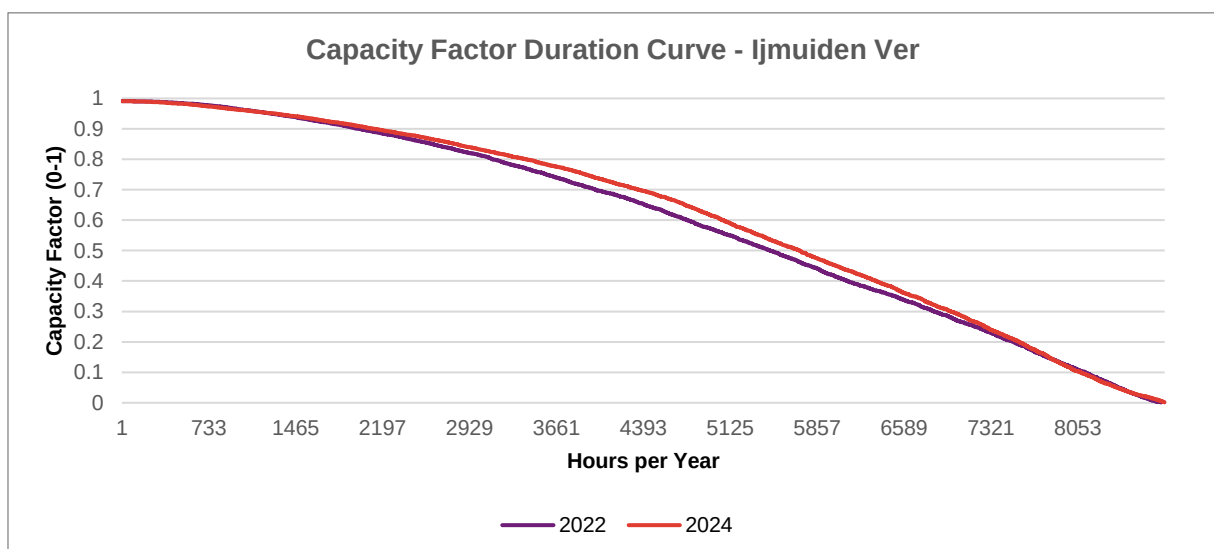


Figure X-6: Capacity Factor Duration Curve - Ijmuiden Ver in 2022 & 2024

Day-ahead Prices

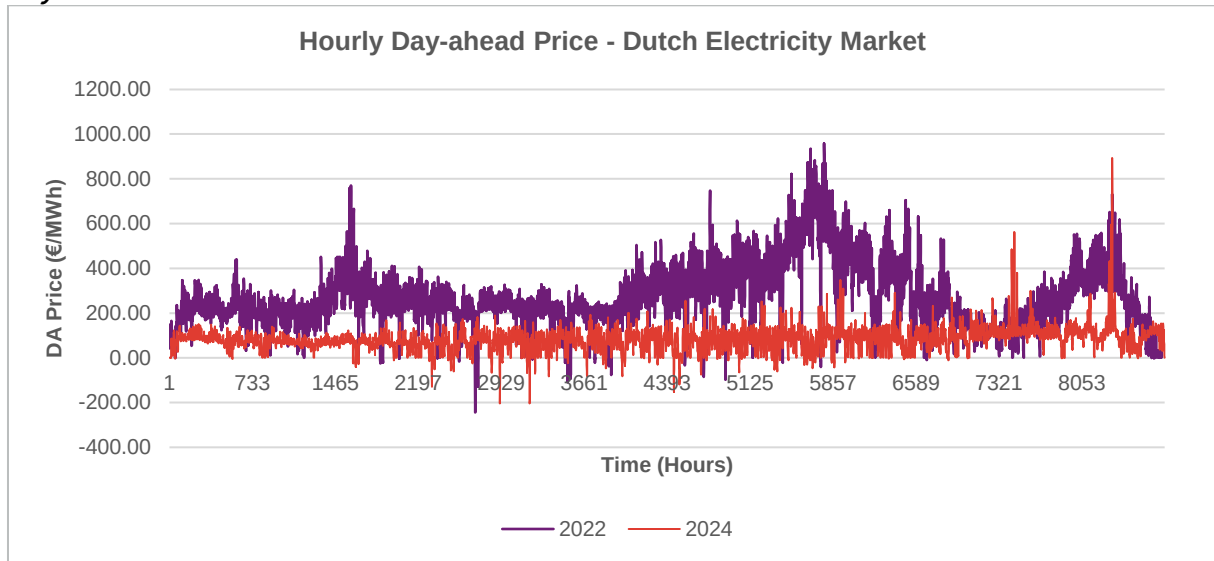


Figure X-7: Hourly Dutch Day-ahead Price in 2022 & 2024

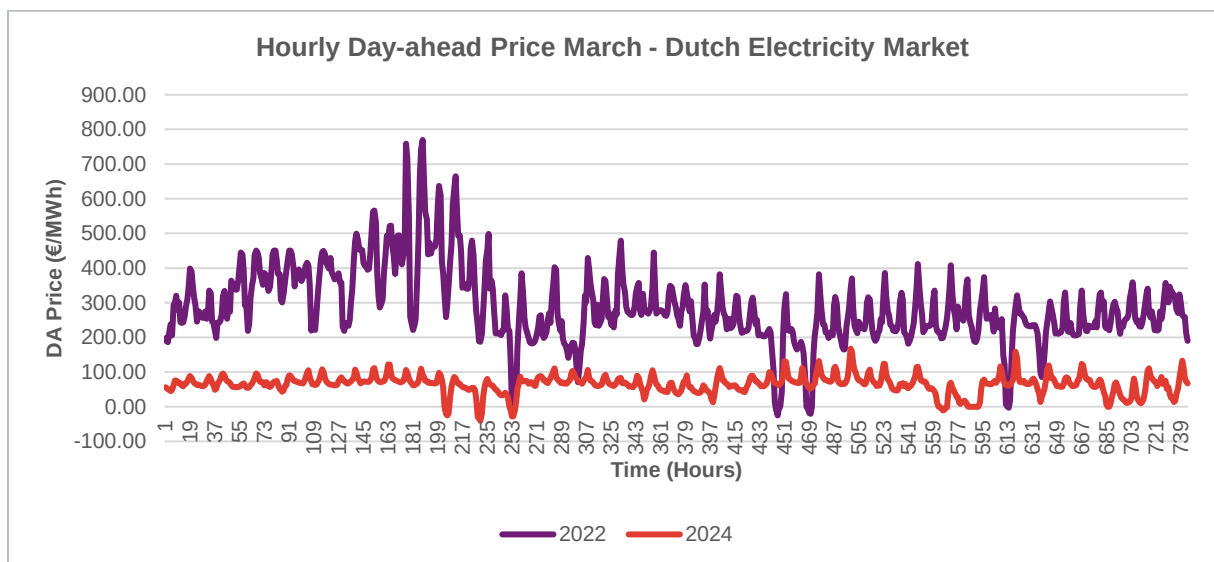


Figure X-8: Hourly Dutch Day-ahead Price in March 2022 & 2024

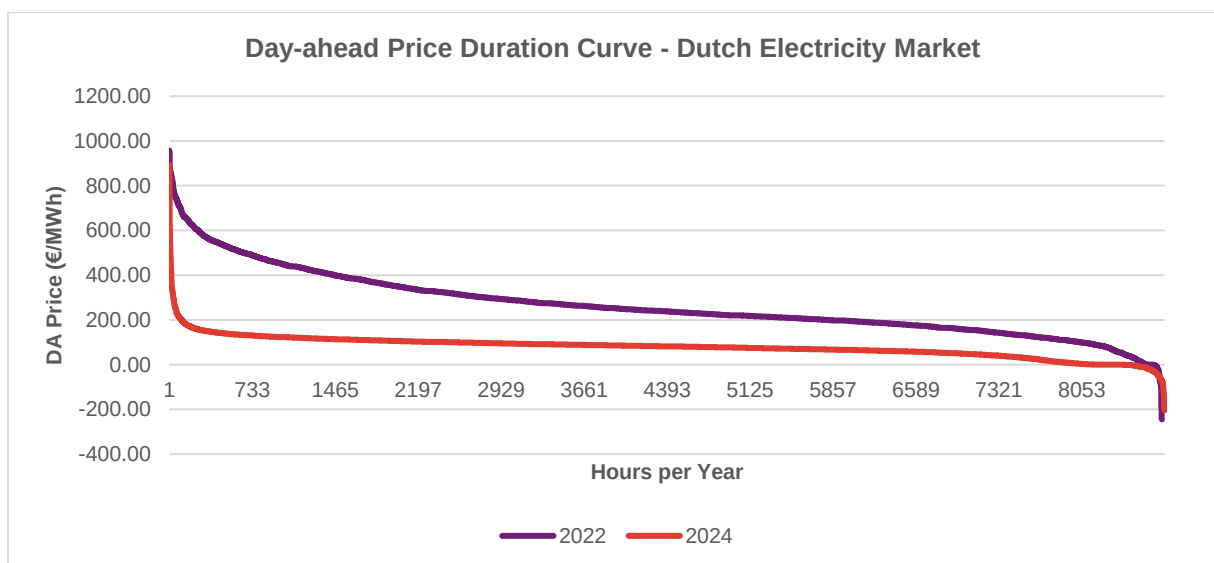


Figure X-9: Dutch Day-ahead Price Duration Curve in 2022 & 2024

Electricity Demand

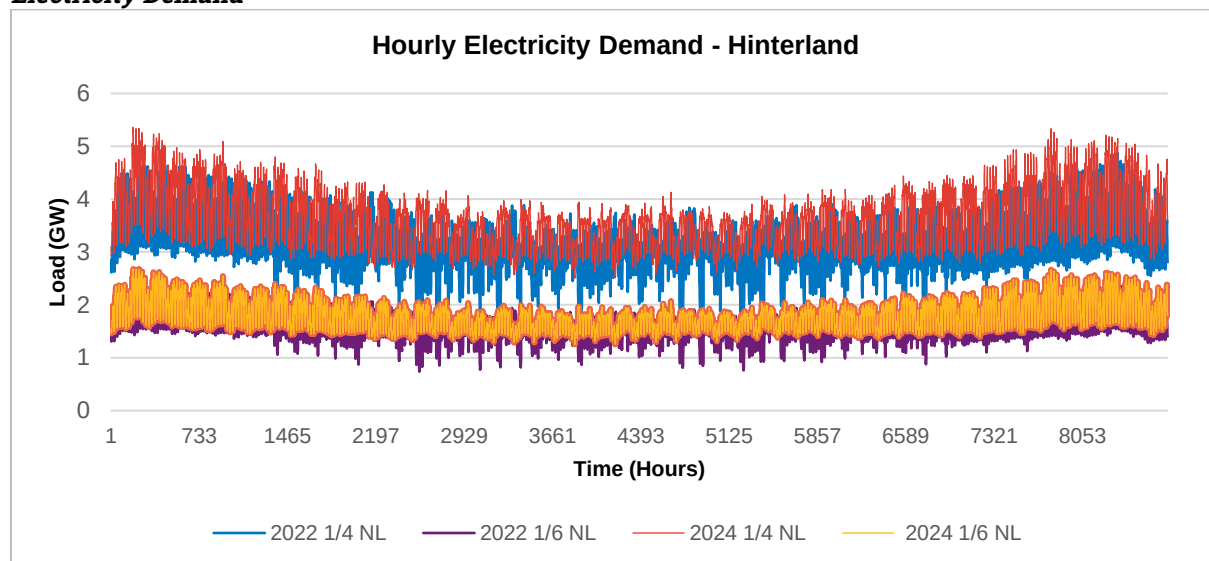


Figure X-10: Hourly Electricity Demand – Dutch Fractions in 2022 & 2024

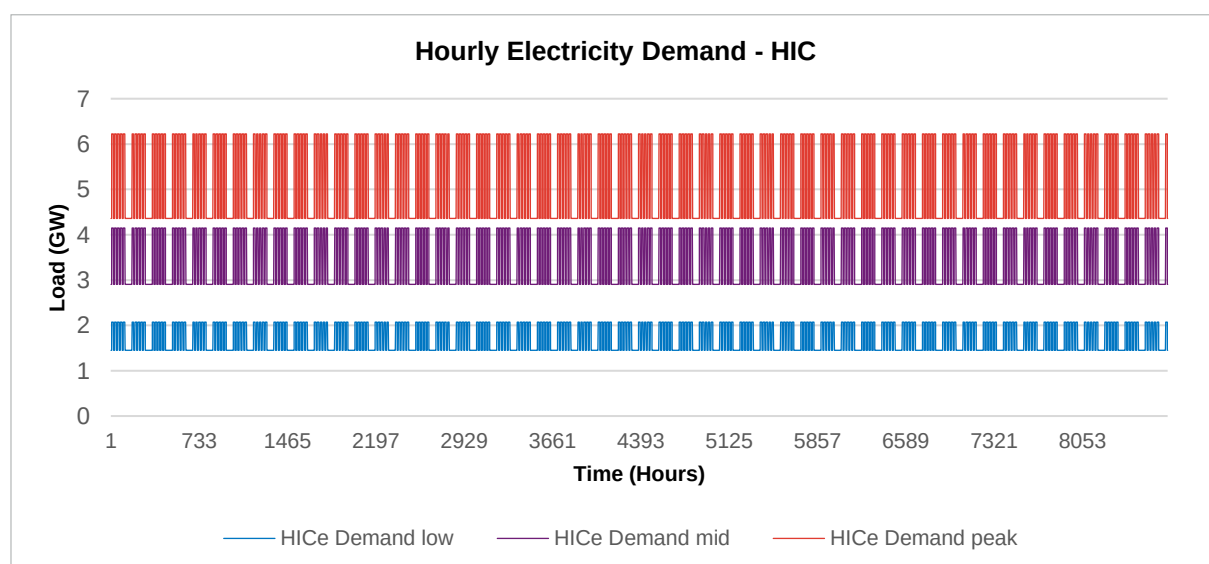


Figure X-11: Hourly Electricity Demand – HIC in 2022 & 2024

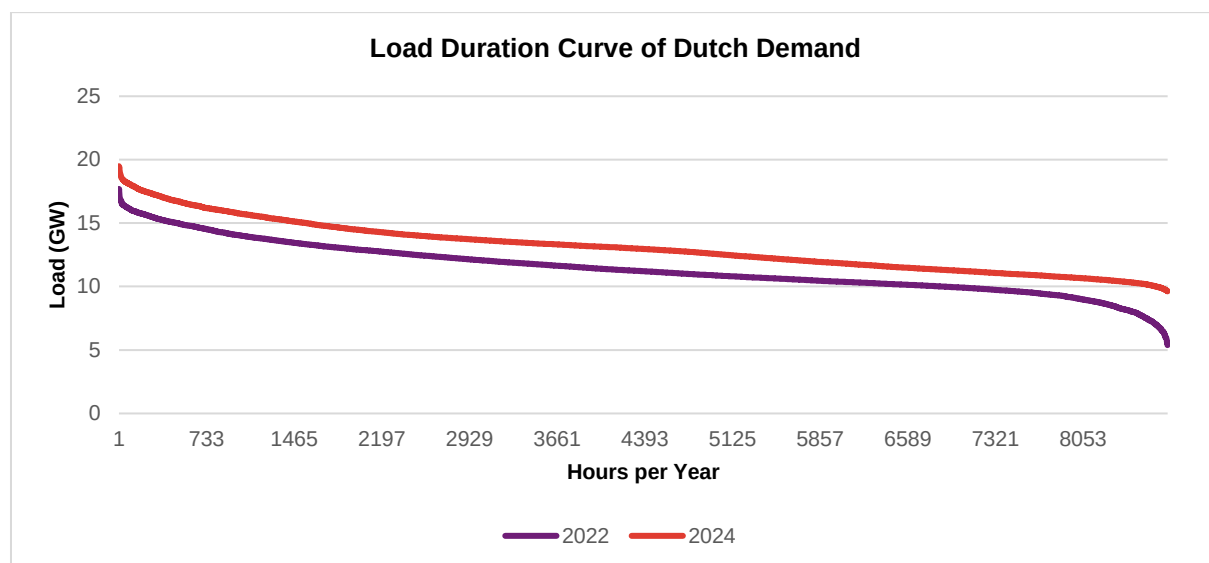


Figure X-12: Load Duration Curve of Dutch Demand in 2022 & 2024

E. Model Results

1. Experiment 1: Base Case & Sensitivity

4 A's

Table X-8: -20% sensitivity of KPIs

		Availability		Accessibility	Acceptability	Affordability			
		EENS	LOLE	H2-E Share	Avg. CO2	LCOH	LCOH	LCOH	Avg. SC
		GWh/year	hours/year	-	ton CO2/GWh	electrolysis €/kg H2	import €/kg H2	Difference €/kg H2	M€/GWh
Base scenario		73.91	116	0.4212	13.44	10.59	8.832	1.757	0.2102
Day Ahead Price 2024	-20%	0%	-2%	4%	1%	0%	0%	-1%	-5%
Installed Grid Supply Capacity 5 GWe	-20%	614%	424%	-3%	-2%	1%	0%	7%	197%
Shipped Green NH3 price 7.70 €/kg H2	-20%	0%	-3%	-12%	-3%	4%	-18%	112%	-2%
HIC Electricity Demand 15 TWhe/year	-20%	-74%	-57%	0%	-5%	0%	0%	-1%	-23%
Hinterland Electricity Demand factor 0.275*Dutch Load 2024	-20%	-100%	-100%	0%	-3%	0%	0%	-1%	-26%
HIC H2 Demand 15 TWh H2/year	-20%	0%	-3%	25%	-6%	0%	1%	-3%	-4%
Hinterland H2 Demand 16.58 TWh H2/year	-20%	0%	-3%	12%	-4%	0%	0%	-1%	-4%
Emission Factor Grid Electricity 35 tCO2/GWhe	-20%	0%	0%	0%	-15%	0%	0%	0%	0%
Emission Factor NH3 Import 16.955 tCO2/GWh H2	-20%	0%	0%	0%	-5%	0%	0%	0%	0%
VoLL 85 M€/GWh	-20%	0%	-2%	0%	0%	0%	0%	0%	-6%
OSW Installed Capacity 7.4 GWe	-20%	23%	9%	-20%	14%	0%	0%	2%	6%
Max. Installed Storage Capacity BESS 5 GWe	-20%	18%	21%	0%	0%	0%	0%	0%	6%
Annualised CAPEX + O&M Electrolyser 433 M€/GWe	-20%	0%	0%	0%	0%	-9%	0%	-53%	-2%
Annualised CAPEX + O&M BESS 27 M€/GWe	-20%	0%	-1%	0%	0%	0%	0%	0%	0%
Annualised CAPEX + O&M H2 Salt Cavern 0.029 M€/GW H2	-20%	0%	-2%	0%	0%	0%	0%	0%	0%
HV fixed Grid Fee 55 M€/GWe/year	-20%	0%	0%	0%	0%	0%	0%	0%	-1%
HV variable Grid Fee 18 €/MWh	-20%	0%	-1%	0%	0%	0%	0%	0%	-1%
HV fixed Grid Fee Electrolyser 55 M€/GWe/year	-20%	0%	0%	0%	0%	-1%	0%	-7%	0%
HV variable Grid Fee Electrolyser 18 €/MWh	-20%	0%	-2%	1%	0%	-2%	0%	-10%	0%
Annual H2 Backbone Tariff (entry fee) 33.09 M€/GW H2	-20%	0%	0%	0%	0%	0%	-1%	0%	0%
Annual H2 Backbone Tariff (exit fee) 33.09 M€/GW H2	-20%	0%	0%	0%	0%	0%	0%	0%	0%
PPA requirement 50%	-20%	0%	-2%	-20%	-6%	0%	0%	2%	-1%
PPA price 80 €/MWh	-20%	0%	-2%	0%	0%	-9%	0%	-54%	-2%
PPA resellability 100%	-20%	11%	3%	1%	0%	0%	0%	0%	3%

Table X-9: +20% sensitivity of KPIs

		Availability		Accessibility	Acceptability	Affordability			
		EENS	LOLE	H2-E Share	Avg. CO2	LCOH	LCOH	LCOH	Avg. SC
		GWh/year	hours/year	-	ton CO2/GWh	electrolysis €/kg H2	import €/kg H2	Difference €/kg H2	M€/GWh
Base scenario		73.91	116	0.4212	13.44	10.59	8.832	1.757	0.2102
Day Ahead Price 2024	20%	0%	-2%	-9%	-2%	0%	0%	2%	5%
Installed Grid Supply Capacity 5 GWe	20%	-100%	-100%	0%	1%	0%	0%	-1%	-33%
Shipped Green NH3 price 7.70 €/kg H2	20%	0%	0%	3%	1%	0%	18%	-91%	3%
HIC Electricity Demand 15 TWhe/year	20%	144%	103%	-1%	4%	0%	0%	2%	43%
Hinterland Electricity Demand factor 0.275*Dutch Load 2024	20%	392%	247%	-2%	2%	1%	0%	4%	102%
HIC H2 Demand 15 TWh H2/year	20%	0%	3%	-17%	5%	0%	0%	2%	4%
Hinterland H2 Demand 16.58 TWh H2/year	20%	0%	-2%	-10%	4%	0%	0%	1%	4%
Emission Factor Grid Electricity 35 tCO2/GWhe	20%	0%	0%	0%	15%	0%	0%	0%	0%
Emission Factor NH3 Import 16.955 tCO2/GWh H2	20%	0%	0%	0%	5%	0%	0%	0%	0%
VoLL 85 M€/GWh	20%	0%	1%	0%	0%	0%	0%	0%	6%
OSW Installed Capacity 7.4 GWe	20%	-19%	-11%	20%	-14%	0%	0%	-3%	-5%
Max. Installed Storage Capacity BESS 5 GWe	20%	-15%	-19%	0%	0%	0%	0%	0%	-5%
Annualised CAPEX + O&M Electrolyser 433 M€/GWe	20%	0%	0%	0%	0%	9%	0%	53%	2%
Annualised CAPEX + O&M BESS 27 M€/GWe	20%	0%	-1%	0%	0%	0%	0%	0%	0%
Annualised CAPEX + O&M H2 Salt Cavern 0.029 M€/GW H2	20%	0%	0%	0%	0%	0%	0%	0%	0%
HV fixed Grid Fee 55 M€/GWe/year	20%	0%	-1%	0%	0%	0%	0%	0%	0%
HV variable Grid Fee 18 €/MWh	20%	0%	-2%	0%	0%	0%	0%	0%	1%
HV fixed Grid Fee Electrolyser 55 M€/GWe/year	20%	0%	0%	0%	0%	1%	0%	7%	0%
HV variable Grid Fee Electrolyser 18 €/MWh	20%	0%	-1%	-1%	0%	2%	0%	10%	0%
Annual H2 Backbone Tarrif (entry fee) 33.09 M€/GW H2	20%	0%	0%	0%	0%	0%	1%	0%	0%
Annual H2 Backbone Tarrif (exit fee) 33.09 M€/GW H2	20%	0%	0%	0%	0%	0%	0%	0%	0%
PPA requirement 50%	20%	0%	-2%	20%	6%	0%	0%	-2%	1%
PPA price 80 €/MWh	20%	0%	-1%	0%	0%	9%	0%	54%	2%
PPA resellability 100%	20%	0%	0%	0%	0%	0%	0%	0%	0%

Operationality

Table X-10: +20% sensitivity of Operational Performance

		Operationality							
		H2 Supply				Storage			
		Installed Capacity Electrolyser GWe	Installed Capacity NH ₃ Cracker GW H2	FLH Electrolyser Hours	FLH NH ₃ Cracker Hours	Installed BESS Capacity GWh	Installed Salt Cavern Capacity GWh H2	Cycle Rate BESS -	Cycle Rate Salt Cavern -
Base scenario		3.667	3.605	5181	5084	5	0	428.4	0
Day Ahead Price 2024	-20%	0%	0%	4%	-3%	0%	0%	-7%	0%
Installed Grid Supply Capacity 5 GWe	-20%	0%	0%	-3%	2%	0%	0%	-6%	0%
Shipped Green NH ₃ price 7.70 €/kg H2	-20%	0%	0%	-12%	9%	0%	0%	0%	0%
HIC Electricity Demand 15 TWh/year	-20%	0%	0%	0%	0%	0%	0%	-1%	0%
Hinterland Electricity Demand factor 0.275*Dutch Load 2024	-20%	0%	0%	0%	0%	-13%	0%	5%	0%
HIC H2 Demand 15 GWh H2/year	-20%	0%	-20%	0%	-18%	0%	0%	0%	0%
Hinterland H2 Demand 16.58 GWh H2/year	-20%	0%	-11%	0%	-9%	0%	0%	0%	0%
Emission Factor Grid Electricity 35 tCO ₂ /GWh	-20%	0%	0%	0%	0%	0%	0%	0%	0%
Emission Factor NH ₃ Import 16.955 tCO ₂ /GWh H2	-20%	0%	0%	0%	0%	0%	0%	0%	0%
VoLL 85 M€/GWh	-20%	0%	0%	0%	0%	0%	0%	0%	0%
OSW Installed Capacity 7.4 GWe	-20%	-20%	0%	0%	15%	0%	0%	-4%	0%
Max. Installed Storage Capacity BESS 5 GWe	-20%	0%	0%	0%	0%	-20%	0%	1%	0%
Annualised CAPEX + O&M Electrolyser 433 M€/GWe	-20%	0%	0%	0%	0%	0%	0%	0%	0%
Annualised CAPEX + O&M BESS 27 M€/GWe	-20%	0%	0%	0%	0%	0%	0%	0%	0%
Annualised CAPEX + O&M H2 Salt Cavern 0.029 M€/GW H2	-20%	0%	0%	0%	0%	0%	0%	0%	0%
HV fixed Grid Fee 55 M€/GWe/year	-20%	0%	0%	0%	0%	0%	0%	0%	0%
HV variable Grid Fee 18 €/MWh	-20%	0%	0%	0%	0%	0%	0%	4%	0%
HV fixed Grid Fee Electrolyser 55 M€/GWe/year	-20%	0%	0%	0%	0%	0%	0%	0%	0%
HV variable Grid Fee Electrolyser 18 €/MWh	-20%	0%	0%	1%	-1%	0%	0%	0%	0%
Annual H2 Backbone Tarrif (entry fee) 33.09 M€/GW H2	-20%	0%	0%	0%	0%	0%	0%	0%	0%
Annual H2 Backbone Tarrif (exit fee) 33.09 M€/GW H2	-20%	0%	0%	0%	0%	0%	0%	0%	0%
PPA requirement 50%	-20%	-20%	0%	0%	15%	0%	0%	1%	0%
PPA price 80 €/MWh	-20%	0%	0%	0%	0%	0%	0%	0%	0%
PPA resellability 100%	-20%	0%	0%	1%	-1%	0%	0%	-1%	0%

Table X-11: -20% sensitivity of Operational Performance

		Operationality							
		H2 Supply				Storage			
		Installed Capacity Electrolyser GWe	Installed Capacity NH ₃ Cracker GW H2	FLH Electrolyser Hours	FLH NH ₃ Cracker Hours	Installed BESS Capacity GWh	Installed Salt Cavern Capacity GWh H2	Cycle Rate BESS -	Cycle Rate Salt Cavern -
Base scenario		3.667	3.605	5181	5084	5	0	428.4	0
Day Ahead Price 2024	20%	0%	0%	-9%	7%	0%	0%	5%	0%
Installed Grid Supply Capacity 5 GWe	20%	0%	0%	0%	0%	-35%	0%	13%	0%
Shipped Green NH ₃ price 7.70 €/kg H2	20%	0%	0%	3%	-3%	0%	0%	0%	0%
HIC Electricity Demand 15 TWh/year	20%	0%	0%	-1%	0%	0%	0%	-10%	0%
Hinterland Electricity Demand factor 0.275*Dutch Load 2024	20%	0%	0%	-2%	1%	0%	0%	-3%	0%
HIC H2 Demand 15 GWh H2/year	20%	0%	20%	0%	12%	0%	0%	0%	0%
Hinterland H2 Demand 16.58 GWh H2/year	20%	0%	11%	0%	7%	0%	0%	0%	0%
Emission Factor Grid Electricity 35 tCO ₂ /GWh	20%	0%	0%	0%	0%	0%	0%	0%	0%
Emission Factor NH ₃ Import 16.955 tCO ₂ /GWh H2	20%	0%	0%	0%	0%	0%	0%	0%	0%
VoLL 85 M€/GWh	20%	0%	0%	0%	0%	0%	0%	0%	0%
OSW Installed Capacity 7.4 GWe	20%	20%	0%	0%	-15%	0%	0%	0%	0%
Max. Installed Storage Capacity BESS 5 GWe	20%	0%	0%	0%	0%	20%	0%	-5%	0%
Annualised CAPEX + O&M Electrolyser 433 M€/GWe	20%	0%	0%	0%	0%	0%	0%	0%	0%
Annualised CAPEX + O&M BESS 27 M€/GWe	20%	0%	0%	0%	0%	0%	0%	0%	0%
Annualised CAPEX + O&M H2 Salt Cavern 0.029 M€/GW H2	20%	0%	0%	0%	0%	0%	0%	0%	0%
HV fixed Grid Fee 55 M€/GWe/year	20%	0%	0%	0%	0%	0%	0%	0%	0%
HV variable Grid Fee 18 €/MWh	20%	0%	0%	0%	0%	0%	0%	-5%	0%
HV fixed Grid Fee Electrolyser 55 M€/GWe/year	20%	0%	0%	0%	0%	0%	0%	0%	0%
HV variable Grid Fee Electrolyser 18 €/MWh	20%	0%	0%	-1%	1%	0%	0%	0%	0%
Annual H2 Backbone Tarrif (entry fee) 33.09 M€/GW H2	20%	0%	0%	0%	0%	0%	0%	0%	0%
Annual H2 Backbone Tarrif (exit fee) 33.09 M€/GW H2	20%	0%	0%	0%	0%	0%	0%	0%	0%
PPA requirement 50%	20%	20%	0%	0%	-14%	0%	0%	-2%	0%
PPA price 80 €/MWh	20%	0%	0%	0%	0%	0%	0%	0%	0%
PPA resellability 100%	20%	0%	0%	0%	0%	0%	0%	0%	0%

2. Experiment 2: Multi-Sensitivity LCOH

		Configurations EENS							Configurations LOLE				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	73.91	73.91	73.91	73.91	73.91	PPA_p_low	NH3_p_low	115	115	115	115	115
	NH3_p_midl	73.91	73.91	73.91	73.91	73.91		NH3_p_midl	112	112	112	112	112
	NH3_p_midm	73.91	73.91	73.91	73.91	73.91		NH3_p_midm	117	117	117	117	117
	NH3_p_midp	73.91	73.91	73.91	73.91	73.91		NH3_p_midp	116	116	116	116	116
	NH3_p_peak	73.91	73.91	73.91	73.91	73.91		NH3_p_peak	113	113	113	113	113
PPA_p_mid	NH3_p_low	73.91	73.91	73.91	73.91	73.91	PPA_p_mid	NH3_p_low	113	113	113	113	113
	NH3_p_midl	73.91	73.91	73.91	73.91	73.91		NH3_p_midl	114	114	114	114	114
	NH3_p_midm	73.91	73.91	73.91	73.91	73.91		NH3_p_midm	116	116	116	116	116
	NH3_p_midp	73.91	73.91	73.91	73.91	73.91		NH3_p_midp	116	116	116	116	116
	NH3_p_peak	73.91	73.91	73.91	73.91	73.91		NH3_p_peak	113	113	113	113	113
PPA_p_peak	NH3_p_low	73.91	73.91	73.91	73.91	73.91	PPA_p_peak	NH3_p_low	113	113	113	113	113
	NH3_p_midl	73.91	73.91	73.91	73.91	73.91		NH3_p_midl	116	116	116	116	116
	NH3_p_midm	73.91	73.91	73.91	73.91	73.91		NH3_p_midm	114	114	114	114	114
	NH3_p_midp	73.91	73.91	73.91	73.91	73.91		NH3_p_midp	116	116	116	116	116
	NH3_p_peak	73.91	73.91	73.91	73.91	73.91		NH3_p_peak	113	113	113	113	113
		Configurations U Rate E							Configurations Avg. CO2				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	0.182	0.182	0.182	0.182	0.182	PPA_p_low	NH3_p_low	11.71	11.71	11.71	11.71	11.71
	NH3_p_midl	0.35	0.35	0.35	0.35	0.35		NH3_p_midl	12.91	12.91	12.91	12.91	12.91
	NH3_p_midm	0.421	0.421	0.421	0.421	0.421		NH3_p_midm	13.44	13.44	13.44	13.44	13.44
	NH3_p_midp	0.437	0.437	0.437	0.437	0.437		NH3_p_midp	13.57	13.57	13.57	13.57	13.57
	NH3_p_peak	0.44	0.44	0.44	0.44	0.44		NH3_p_peak	13.59	13.59	13.59	13.59	13.59
PPA_p_mid	NH3_p_low	0.182	0.182	0.182	0.182	0.182	PPA_p_mid	NH3_p_low	11.71	11.71	11.71	11.71	11.71
	NH3_p_midl	0.35	0.35	0.35	0.35	0.35		NH3_p_midl	12.91	12.91	12.91	12.91	12.91
	NH3_p_midm	0.421	0.421	0.421	0.421	0.421		NH3_p_midm	13.44	13.44	13.44	13.44	13.44
	NH3_p_midp	0.437	0.437	0.437	0.437	0.437		NH3_p_midp	13.57	13.57	13.57	13.57	13.57
	NH3_p_peak	0.44	0.44	0.44	0.44	0.44		NH3_p_peak	13.59	13.59	13.59	13.59	13.59
PPA_p_peak	NH3_p_low	0.182	0.182	0.182	0.182	0.182	PPA_p_peak	NH3_p_low	11.71	11.71	11.71	11.71	11.71
	NH3_p_midl	0.35	0.35	0.35	0.35	0.35		NH3_p_midl	12.91	12.91	12.91	12.91	12.91
	NH3_p_midm	0.421	0.421	0.421	0.421	0.421		NH3_p_midm	13.44	13.44	13.44	13.44	13.44
	NH3_p_midp	0.437	0.437	0.437	0.437	0.437		NH3_p_midp	13.57	13.57	13.57	13.57	13.57
	NH3_p_peak	0.44	0.44	0.44	0.44	0.44		NH3_p_peak	13.59	13.59	13.59	13.59	13.59
		Configurations LCOHe							Configurations LCOHi				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	0.12	2.83	5.55	8.26	10.97	PPA_p_low	NH3_p_low	4.91	4.91	4.91	4.91	4.91
	NH3_p_midl	2.75	4.16	5.57	6.98	8.39		NH3_p_midl	6.88	6.88	6.88	6.88	6.88
	NH3_p_midm	3.53	4.71	5.88	7.05	8.23		NH3_p_midm	8.83	8.83	8.83	8.83	8.83
	NH3_p_midp	3.74	4.87	6	7.13	8.26		NH3_p_midp	10.76	10.76	10.76	10.76	10.76
	NH3_p_peak	3.79	4.91	6.03	7.16	8.28		NH3_p_peak	12.69	12.69	12.69	12.69	12.69
PPA_p_mid	NH3_p_low	5.58	8.29	11.01	13.72	16.43	PPA_p_mid	NH3_p_low	4.91	4.91	4.91	4.91	4.91
	NH3_p_midl	5.59	7	8.41	9.82	11.23		NH3_p_midl	6.88	6.88	6.88	6.88	6.88
	NH3_p_midm	5.89	7.07	8.24	9.41	10.59		NH3_p_midm	8.83	8.83	8.83	8.83	8.83
	NH3_p_midp	6.02	7.15	8.28	9.41	10.54		NH3_p_midp	10.76	10.76	10.76	10.76	10.76
	NH3_p_peak	6.05	7.17	8.29	9.42	10.54		NH3_p_peak	12.69	12.69	12.69	12.69	12.69
PPA_p_peak	NH3_p_low	11.04	13.76	16.47	19.18	21.89	PPA_p_peak	NH3_p_low	4.91	4.91	4.91	4.91	4.91
	NH3_p_midl	8.43	9.84	11.25	12.66	14.08		NH3_p_midl	6.88	6.88	6.88	6.88	6.88
	NH3_p_midm	8.26	9.43	10.61	11.78	12.95		NH3_p_midm	8.83	8.83	8.83	8.83	8.83
	NH3_p_midp	8.29	9.42	10.55	11.68	12.81		NH3_p_midp	10.76	10.76	10.76	10.76	10.76
	NH3_p_peak	8.31	9.43	10.56	11.68	12.8		NH3_p_peak	12.69	12.69	12.69	12.69	12.69
		Configurations LCOH Difference							Configurations Avg. SC				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	-4.79	-2.08	0.64	3.35	6.06	PPA_p_low	NH3_p_low	0.173	0.178	0.182	0.186	0.19
	NH3_p_midl	-4.13	-2.72	-1.31	0.1	1.51		NH3_p_midl	0.178	0.183	0.187	0.191	0.196
	NH3_p_midm	-5.3	-4.13	-2.95	-1.78	-0.61		NH3_p_midm	0.185	0.189	0.193	0.197	0.202
	NH3_p_midp	-7.02	-5.89	-4.76	-3.63	-2.5		NH3_p_midp	0.193	0.197	0.201	0.206	0.21
	NH3_p_peak	-8.9	-7.78	-6.66	-5.53	-4.41		NH3_p_peak	0.202	0.206	0.21	0.215	0.219
PPA_p_mid	NH3_p_low	0.67	3.39	6.1	8.81	11.52	PPA_p_mid	NH3_p_low	0.182	0.186	0.19	0.195	0.199
	NH3_p_midl	-1.29	0.12	1.53	2.94	4.35		NH3_p_midl	0.187	0.191	0.196	0.2	0.204
	NH3_p_midm	-2.94	-1.76	-0.59	0.58	1.76		NH3_p_midm	0.193	0.197	0.202	0.206	0.21
	NH3_p_midp	-4.75	-3.62	-2.49	-1.36	-0.23		NH3_p_midp	0.201	0.206	0.21	0.214	0.218
	NH3_p_peak	-6.64	-5.52	-4.39	-3.27	-2.15		NH3_p_peak	0.21	0.215	0.219	0.223	0.228
PPA_p_peak	NH3_p_low	6.13	8.85	11.56	14.27	16.98	PPA_p_peak	NH3_p_low	0.191	0.195	0.199	0.203	0.208
	NH3_p_midl	1.55	2.96	4.37	5.78	7.2		NH3_p_midl	0.196	0.2	0.204	0.208	0.213
	NH3_p_midm	-0.57	0.6	1.77	2.95	4.12		NH3_p_midm	0.202	0.206	0.21	0.214	0.219
	NH3_p_midp	-2.47	-1.34	-0.21	0.92	2.05		NH3_p_midp	0.21	0.214	0.218	0.223	0.227
	NH3_p_peak	-4.38	-3.26	-2.13	-1.01	0.11		NH3_p_peak	0.219	0.223	0.228	0.232	0.236

		Configurations Installed Capacity Electrolysis							Configurations Installed Capacity NH3 Cracking				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	3.667	3.667	3.667	3.667	3.667	PPA_p_low	NH3_p_low	3.605	3.605	3.605	3.605	3.605
	NH3_p_midl	3.667	3.667	3.667	3.667	3.667		NH3_p_midl	3.605	3.605	3.605	3.605	3.605
	NH3_p_midm	3.667	3.667	3.667	3.667	3.667		NH3_p_midm	3.605	3.605	3.605	3.605	3.605
	NH3_p_midp	3.667	3.667	3.667	3.667	3.667		NH3_p_midp	3.605	3.605	3.605	3.605	3.605
	NH3_p_peak	3.667	3.667	3.667	3.667	3.667		NH3_p_peak	3.605	3.605	3.605	3.605	3.605
PPA_p_mid	NH3_p_low	3.667	3.667	3.667	3.667	3.667	PPA_p_mid	NH3_p_low	3.605	3.605	3.605	3.605	3.605
	NH3_p_midl	3.667	3.667	3.667	3.667	3.667		NH3_p_midl	3.605	3.605	3.605	3.605	3.605
	NH3_p_midm	3.667	3.667	3.667	3.667	3.667		NH3_p_midm	3.605	3.605	3.605	3.605	3.605
	NH3_p_midp	3.667	3.667	3.667	3.667	3.667		NH3_p_midp	3.605	3.605	3.605	3.605	3.605
	NH3_p_peak	3.667	3.667	3.667	3.667	3.667		NH3_p_peak	3.605	3.605	3.605	3.605	3.605
PPA_p_peak	NH3_p_low	3.667	3.667	3.667	3.667	3.667	PPA_p_peak	NH3_p_low	3.605	3.605	3.605	3.605	3.605
	NH3_p_midl	3.667	3.667	3.667	3.667	3.667		NH3_p_midl	3.605	3.605	3.605	3.605	3.605
	NH3_p_midm	3.667	3.667	3.667	3.667	3.667		NH3_p_midm	3.605	3.605	3.605	3.605	3.605
	NH3_p_midp	3.667	3.667	3.667	3.667	3.667		NH3_p_midp	3.605	3.605	3.605	3.605	3.605
	NH3_p_peak	3.667	3.667	3.667	3.667	3.667		NH3_p_peak	3.605	3.605	3.605	3.605	3.605
		Configurations FLH Electrolysis							Configurations FLH NH3 Cracking				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	2242	2242	2242	2242	2242	PPA_p_low	NH3_p_low	7182	7182	7182	7182	7182
	NH3_p_midl	4308	4308	4308	4308	4308		NH3_p_midl	5707	5707	5707	5707	5707
	NH3_p_midm	5180	5180	5180	5180	5180		NH3_p_midm	5084	5084	5084	5084	5084
	NH3_p_midp	5378	5378	5378	5378	5378		NH3_p_midp	4942	4942	4942	4942	4942
	NH3_p_peak	5414	5414	5414	5414	5414		NH3_p_peak	4917	4917	4917	4917	4917
PPA_p_mid	NH3_p_low	2242	2242	2242	2242	2242	PPA_p_mid	NH3_p_low	7182	7182	7182	7182	7182
	NH3_p_midl	4308	4308	4308	4308	4308		NH3_p_midl	5707	5707	5707	5707	5707
	NH3_p_midm	5180	5180	5180	5180	5180		NH3_p_midm	5084	5084	5084	5084	5084
	NH3_p_midp	5378	5378	5378	5378	5378		NH3_p_midp	4942	4942	4942	4942	4942
	NH3_p_peak	5414	5414	5414	5414	5414		NH3_p_peak	4917	4917	4917	4917	4917
PPA_p_peak	NH3_p_low	2242	2242	2242	2242	2242	PPA_p_peak	NH3_p_low	7182	7182	7182	7182	7182
	NH3_p_midl	4308	4308	4308	4308	4308		NH3_p_midl	5707	5707	5707	5707	5707
	NH3_p_midm	5180	5180	5180	5180	5180		NH3_p_midm	5084	5084	5084	5084	5084
	NH3_p_midp	5378	5378	5378	5378	5378		NH3_p_midp	4942	4942	4942	4942	4942
	NH3_p_peak	5414	5414	5414	5414	5414		NH3_p_peak	4917	4917	4917	4917	4917
		Configurations Installed Storage Capacity BESS							Configurations Installed Storage Capacity Salt Cavern				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	5	5	5	5	5	PPA_p_low	NH3_p_low	0	0	0	0	0
	NH3_p_midl	5	5	5	5	5		NH3_p_midl	0	0	0	0	0
	NH3_p_midm	5	5	5	5	5		NH3_p_midm	0	0	0	0	0
	NH3_p_midp	5	5	5	5	5		NH3_p_midp	0	0	0	0	0
	NH3_p_peak	5	5	5	5	5		NH3_p_peak	0	0	0	0	0
PPA_p_mid	NH3_p_low	5	5	5	5	5	PPA_p_mid	NH3_p_low	0	0	0	0	0
	NH3_p_midl	5	5	5	5	5		NH3_p_midl	0	0	0	0	0
	NH3_p_midm	5	5	5	5	5		NH3_p_midm	0	0	0	0	0
	NH3_p_midp	5	5	5	5	5		NH3_p_midp	0	0	0	0	0
	NH3_p_peak	5	5	5	5	5		NH3_p_peak	0	0	0	0	0
PPA_p_peak	NH3_p_low	5	5	5	5	5	PPA_p_peak	NH3_p_low	0	0	0	0	0
	NH3_p_midl	5	5	5	5	5		NH3_p_midl	0	0	0	0	0
	NH3_p_midm	5	5	5	5	5		NH3_p_midm	0	0	0	0	0
	NH3_p_midp	5	5	5	5	5		NH3_p_midp	0	0	0	0	0
	NH3_p_peak	5	5	5	5	5		NH3_p_peak	0	0	0	0	0
		Configurations Cycle Rate BESS							Configurations Cycle Rate Salt Cavern				
		EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak			EL_CO_0	EL_CO_low	EL_CO_midl	EL_CO_midp	EL_CO_peak
PPA_p_low	NH3_p_low	441	441	441	441	441	PPA_p_low	NH3_p_low	0	0	0	0	0
	NH3_p_midl	430	430	430	430	430		NH3_p_midl	0	0	0	0	0
	NH3_p_midm	428	428	428	428	428		NH3_p_midm	0	0	0	0	0
	NH3_p_midp	428	428	428	428	428		NH3_p_midp	0	0	0	0	0
	NH3_p_peak	428	428	428	428	428		NH3_p_peak	0	0	0	0	0
PPA_p_mid	NH3_p_low	441	441	441	441	441	PPA_p_mid	NH3_p_low	0	0	0	0	0
	NH3_p_midl	430	430	430	430	430		NH3_p_midl	0	0	0	0	0
	NH3_p_midm	428	428	428	428	428		NH3_p_midm	0	0	0	0	0
	NH3_p_midp	428	428	428	428	428		NH3_p_midp	0	0	0	0	0
	NH3_p_peak	428	428	428	428	428		NH3_p_peak	0	0	0	0	0
PPA_p_peak	NH3_p_low	441	441	441	441	441	PPA_p_peak	NH3_p_low	0	0	0	0	0
	NH3_p_midl	430	430	430	430	430		NH3_p_midl	0	0	0	0	0
	NH3_p_midm	428	428	428	428	428		NH3_p_midm	0	0	0	0	0
	NH3_p_midp	428	428	428	428	428		NH3_p_midp	0	0	0	0	0
	NH3_p_peak	428	428	428	428	428		NH3_p_peak	0	0	0	0	0

3. Experiment 3: System Flexibility & Resilience

			Configurations EENS													Configurations LOLE									
			Wind_low					Wind_peak								Wind_low					Wind_peak				
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW
HIN_E_lo w	HIC_H_lo w	GRID_4.0 GW	864	523	151	40	7	357	173	16	0	0	HIN_E_lo w	HIC_H_lo w	GRID_4.0 GW	1024	590	172	50	13	436	245	24	0	0
		GRID_4.5 GW	464	223	23	0	0	194	59	0	0	0			GRID_4.5 GW	577	305	32	0	0	240	97	0	0	0
		GRID_5.0 GW	230	65	0	0	0	98	17	0	0	0			GRID_5.0 GW	380	111	0	0	0	158	30	0	0	0
		GRID_5.5 GW	79	7	0	0	0	34	2	0	0	0			GRID_5.5 GW	214	16	0	0	0	88	3	0	0	0
		GRID_6.0 GW	12	0	0	0	0	5	0	0	0	0			GRID_6.0 GW	59	0	0	0	0	31	0	0	0	0
	HIC_H_pe ak	GRID_4.0 GW	864	523	151	40	7	357	173	16	0	0		HIC_H_pe ak	GRID_4.0 GW	1024	585	174	53	12	436	246	24	0	0
		GRID_4.5 GW	464	223	23	0	0	194	59	0	0	0			GRID_4.5 GW	577	307	31	0	0	240	97	0	0	0
		GRID_5.0 GW	230	65	0	0	0	98	17	0	0	0			GRID_5.0 GW	380	114	0	0	0	158	32	0	0	0
		GRID_5.5 GW	79	7	0	0	0	34	2	0	0	0			GRID_5.5 GW	214	15	0	0	0	88	3	0	0	0
		GRID_6.0 GW	12	0	0	0	0	5	0	0	0	0			GRID_6.0 GW	59	0	0	0	0	31	0	0	0	0
HIN_E_pe ak	HIC_H_lo w	GRID_4.0 GW	4084	3434	2311	1711	1292	1660	1292	666	363	206	HIN_E_pe ak	HIC_H_lo w	GRID_4.0 GW	2472	2088	1223	893	680	967	813	358	192	119
		GRID_4.5 GW	2949	2362	1440	968	730	1211	886	380	180	77			GRID_4.5 GW	2058	1631	855	570	438	827	629	240	113	54
		GRID_5.0 GW	2019	1513	799	489	301	838	567	192	74	19			GRID_5.0 GW	1655	1211	533	356	217	675	457	139	55	14
		GRID_5.5 GW	1300	882	364	170	70	538	328	84	15	0			GRID_5.5 GW	1230	809	301	133	71	503	315	69	11	1
		GRID_6.0 GW	791	465	120	32	9	333	164	20	0	0			GRID_6.0 GW	815	479	99	31	11	330	206	25	0	0
	HIC_H_pe ak	GRID_4.0 GW	4084	3434	2311	1711	1292	1660	1292	666	363	206		HIC_H_pe ak	GRID_4.0 GW	2472	2093	1239	914	669	967	815	329	192	115
		GRID_4.5 GW	2949	2362	1440	968	730	1211	886	380	180	77			GRID_4.5 GW	2058	1631	865	560	441	827	625	214	113	50
		GRID_5.0 GW	2019	1513	799	489	301	838	567	192	74	19			GRID_5.0 GW	1655	1211	550	351	219	675	484	138	52	13
		GRID_5.5 GW	1300	882	364	170	70	538	328	84	15	0			GRID_5.5 GW	1230	812	302	152	68	503	325	69	10	1
		GRID_6.0 GW	791	465	120	32	9	333	164	20	0	0			GRID_6.0 GW	815	480	96	31	9	330	210	25	0	0
			Configurations U Rate E													Configurations Avg. CO2									
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW
HIN_E_lo w	HIC_H_lo w	GRID_4.0 GW	0.408	0.41	0.416	0.422	0.424	0.96	0.961	0.97	0.973	0.973	HIN_E_lo w	HIC_H_lo w	GRID_4.0 GW	17.69	15.6	16.31	16.45	16.53	4.34	4.38	4.66	4.75	4.75
		GRID_4.5 GW	0.415	0.417	0.423	0.429	0.429	0.961	0.963	0.971	0.972	0.972			GRID_4.5 GW	18.77	15.84	16.54	16.82	16.82	4.57	4.54	4.85	4.88	4.88
		GRID_5.0 GW	0.419	0.421	0.426	0.429	0.429	0.962	0.964	0.97	0.971	0.971			GRID_5.0 GW	19.33	16	16.74	16.88	16.88	4.63	4.64	4.9	4.92	4.92
		GRID_5.5 GW	0.422	0.422	0.425	0.425	0.425	0.963	0.964	0.967	0.967	0.967			GRID_5.5 GW	19.68	16.13	16.55	16.59	16.59	4.72	4.84	4.96	4.96	4.96
		GRID_6.0 GW	0.423	0.423	0.423	0.423	0.423	0.963	0.964	0.964	0.964	0.964			GRID_6.0 GW	20.25	16.16	16.21	16.21	16.21	4.76	4.81	4.82	4.81	4.81
	HIC_H_pe ak	GRID_4.0 GW	0.102	0.103	0.104	0.105	0.106	0.277	0.279	0.284	0.286	0.286		HIC_H_pe ak	GRID_4.0 GW	24.35	23.04	23.48	23.57	23.62	15.61	15.44	15.74	15.89	15.89
		GRID_4.5 GW	0.104	0.104	0.106	0.107	0.107	0.278	0.279	0.284	0.285	0.285			GRID_4.5 GW	25.04	23.19	23.63	23.81	23.81	15.79	15.55	15.83	15.88	15.88
		GRID_5.0 GW	0.105	0.105	0.107	0.107	0.107	0.279	0.28	0.284	0.284	0.284			GRID_5.0 GW	25.39	23.29	23.76	23.85	23.85	15.86	15.61	15.84	15.86	15.86
		GRID_5.5 GW	0.105	0.106	0.106	0.106	0.106	0.279	0.28	0.282	0.282	0.282			GRID_5.5 GW	25.61	23.37	23.64	23.66	23.66	15.99	15.73	15.84	15.84	15.84
		GRID_6.0 GW	0.106	0.106	0.106	0.106	0.106	0.279	0.28	0.28	0.28	0.28			GRID_6.0 GW	25.97	23.39	23.42	23.42	23.42	16	15.71	15.72	15.72	15.72
HIN_E_pe ak	HIC_H_lo w	GRID_4.0 GW	0.323	0.325	0.316	0.309	0.303	0.946	0.947	0.952	0.957	0.96	HIN_E_pe ak	HIC_H_lo w	GRID_4.0 GW	15.5	15.13	15.09	15.03	14.97	4.89	4.96	5.59	5.95	5.39
		GRID_4.5 GW	0.356	0.36	0.36	0.357	0.358	0.95	0.952	0.957	0.963	0.965			GRID_4.5 GW	16.15	15.51	15.58	15.6	15.6	5.02	5.08	5.59	5.75	5.67
		GRID_5.0 GW	0.382	0.386	0.388	0.39	0.393	0.954	0.956	0.96	0.967	0.97			GRID_5.0 GW	16.93	15.81	15.92	16.08	16.1	5.15	5.22	5.56	5.85	5.96
		GRID_5.5 GW	0.399	0.403	0.405	0.411	0.413	0.957	0.958	0.964	0.97	0.972			GRID_5.5 GW	17.63	16.02	16.15	16.48	16.49	5.25	5.3	5.74	6.09	6.22
		GRID_6.0 GW	0.409	0.412	0.414	0.421	0.424	0.959	0.96	0.965	0.972	0.972			GRID_6.0 GW	18.47	16.2	16.33	16.7	16.77	5.4	5.43	5.92	6.27	6.27
	HIC_H_pe ak	GRID_4.0 GW	0.081	0.081	0.079	0.077	0.076	0.271	0.272	0.275	0.279	0.28		HIC_H_pe ak	GRID_4.0 GW	21.43	21.17	21.15	21.1	21.06	13.68	13.64	14.34	14.6	14.24
		GRID_4.5 GW	0.089	0.09	0.09	0.089	0.089	0.273	0.274	0.277	0.281	0.282			GRID_4.5 GW	21.9	21.45	21.49	21.5	21.51	13.83	13.77	14.32	14.44	14.48
		GRID_5.0 GW	0.095	0.097	0.097	0.098	0.098	0.274	0.275	0.279	0.283	0.284			GRID_5.0 GW	22.45	21.66	21.73	21.84	21.86	14	13.85	14.19	14.6	14.69
		GRID_5.5 GW	0.1	0.101	0.101	0.103	0.103	0.275	0.276	0.28	0.284	0.285			GRID_5.5 GW	22.94	21.8	21.89	22.12	22.13	14.13	13.96	14.31	14.79	14.9
		GRID_6.0 GW	0.102	0.103	0.104	0.105	0.106	0.276	0.277	0.281	0.285	0.285			GRID_6.0 GW	23.53	21.93	22.02	22.28	22.33	14.27	14.02	14.43	14.87	14.87

			Configurations LCOHe										Configurations LCOHi												
			Wind_low					Wind_peak								Wind_low					Wind_peak				
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW
HIN_E_lo w	HIC_H_lo w	GRID_4_0 GW	10.75	10.71	10.68	10.65	10.62	11.19	11.2	11.2	11.2	11.2	HIC_H_lo w	GRID_4_0 GW	8.83	8.83	8.83	8.83	8.83	9.75	9.78	9.92	10.01	10.01	
		GRID_4_5 GW	10.66	10.63	10.61	10.58	10.58	11.18	11.18	11.19	11.19	11.19		GRID_4_5 GW	8.83	8.83	8.83	8.84	8.84	9.78	9.82	9.94	9.99	9.99	
		GRID_5_0 GW	10.61	10.6	10.58	10.57	10.57	11.18	11.18	11.18	11.18	11.18		GRID_5_0 GW	8.83	8.83	8.84	8.84	8.84	9.8	9.83	9.94	9.98	9.98	
		GRID_5_5 GW	10.59	10.58	10.57	10.57	10.57	11.17	11.18	11.18	11.18	11.18		GRID_5_5 GW	8.83	8.83	8.83	8.83	8.83	9.81	9.82	9.9	9.9	9.9	
		GRID_6_0 GW	10.57	10.57	10.57	10.57	10.57	11.17	11.17	11.17	11.17	11.17		GRID_6_0 GW	8.83	8.83	8.83	8.83	8.83	9.81	9.82	9.83	9.83	9.83	
	HIC_H_pe ak	GRID_4_0 GW	10.75	10.71	10.68	10.64	10.62	10.59	10.58	10.56	10.55	10.55	HIC_H_pe ak	GRID_4_0 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_4_5 GW	10.66	10.63	10.61	10.58	10.58	10.58	10.57	10.55	10.55	10.55		GRID_4_5 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_5_0 GW	10.61	10.6	10.58	10.57	10.57	10.57	10.56	10.55	10.55	10.55		GRID_5_0 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_5_5 GW	10.59	10.58	10.57	10.57	10.57	10.57	10.56	10.56	10.56	10.56		GRID_5_5 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_6_0 GW	10.57	10.57	10.57	10.57	10.57	10.57	10.56	10.56	10.56	10.56		GRID_6_0 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
HIN_E_pe ak	HIC_H_lo w	GRID_4_0 GW	12.15	12.08	12.26	12.42	12.56	11.24	11.24	11.24	11.24	11.22	HIC_H_lo w	GRID_4_0 GW	8.79	8.8	8.79	8.79	8.79	9.64	9.68	9.76	9.88	9.96	
		GRID_4_5 GW	11.5	11.41	11.42	11.46	11.46	11.21	11.21	11.21	11.21	11.2		GRID_4_5 GW	8.81	8.81	8.81	8.81	8.81	9.68	9.71	9.8	9.94	10.01	
		GRID_5_0 GW	11.09	11.01	10.99	10.97	10.95	11.18	11.18	11.19	11.18	11.18		GRID_5_0 GW	8.82	8.82	8.82	8.82	8.82	9.71	9.73	9.84	10.01	10.1	
		GRID_5_5 GW	10.86	10.8	10.77	10.73	10.71	11.17	11.16	11.17	11.17	11.17		GRID_5_5 GW	8.82	8.82	8.82	8.83	8.83	9.74	9.76	9.89	10.05	10.11	
		GRID_6_0 GW	10.72	10.68	10.66	10.63	10.61	11.15	11.15	11.16	11.16	11.16		GRID_6_0 GW	8.83	8.83	8.83	8.83	8.83	9.77	9.8	9.92	10.06	10.06	
	HIC_H_pe ak	GRID_4_0 GW	12.15	12.08	12.27	12.41	12.56	10.69	10.68	10.65	10.63	10.61	HIC_H_pe ak	GRID_4_0 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_4_5 GW	11.5	11.41	11.41	11.46	11.46	10.66	10.64	10.62	10.6	10.59		GRID_4_5 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_5_0 GW	11.09	11.01	10.99	10.97	10.95	10.63	10.62	10.6	10.58	10.57		GRID_5_0 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_5_5 GW	10.86	10.8	10.77	10.73	10.71	10.61	10.6	10.58	10.56	10.55		GRID_5_5 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
		GRID_6_0 GW	10.72	10.68	10.66	10.63	10.61	10.59	10.59	10.57	10.56	10.56		GRID_6_0 GW	8.74	8.74	8.74	8.74	8.74	8.78	8.78	8.78	8.78	8.78	
			Configurations LCOH Difference													Configurations Avg. SC									
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW
HIN_E_lo w	HIC_H_lo w	GRID_4_0 GW	1.925	1.887	1.846	1.813	1.786	1.446	1.414	1.281	1.192	1.193	HIC_H_lo w	GRID_4_0 GW	1.124	0.752	0.35	0.232	0.201	0.595	0.395	0.23	0.217	0.217	
		GRID_4_5 GW	1.829	1.804	1.774	1.745	1.745	1.403	1.368	1.254	1.199	1.199		GRID_4_5 GW	0.681	0.419	0.207	0.187	0.187	0.414	0.268	0.211	0.211	0.211	
		GRID_5_0 GW	1.78	1.763	1.745	1.739	1.739	1.379	1.352	1.235	1.198	1.198		GRID_5_0 GW	0.422	0.244	0.18	0.18	0.18	0.307	0.223	0.208	0.208	0.208	
		GRID_5_5 GW	1.753	1.743	1.737	1.736	1.736	1.367	1.353	1.277	1.277	1.277		GRID_5_5 GW	0.256	0.18	0.175	0.175	0.175	0.236	0.205	0.204	0.204	0.204	
		GRID_6_0 GW	1.742	1.741	1.741	1.741	1.741	1.362	1.352	1.342	1.342	1.342		GRID_6_0 GW	0.181	0.17	0.17	0.17	0.17	0.205	0.201	0.201	0.201	0.201	
	HIC_H_pe ak	GRID_4_0 GW	2.01	1.973	1.934	1.903	1.878	1.811	1.8	1.778	1.769	1.769	HIC_H_pe ak	GRID_4_0 GW	0.884	0.649	0.397	0.322	0.302	0.542	0.416	0.313	0.304	0.304	
		GRID_4_5 GW	1.917	1.893	1.865	1.839	1.839	1.798	1.79	1.771	1.769	1.769		GRID_4_5 GW	0.605	0.44	0.306	0.294	0.294	0.428	0.336	0.3	0.3	0.3	
		GRID_5_0 GW	1.87	1.853	1.838	1.833	1.832	1.791	1.783	1.77	1.768	1.769		GRID_5_0 GW	0.442	0.329	0.289	0.289	0.289	0.361	0.307	0.298	0.298	0.298	
		GRID_5_5 GW	1.843	1.835	1.829	1.828	1.828	1.786	1.781	1.773	1.773	1.773		GRID_5_5 GW	0.337	0.289	0.286	0.286	0.286	0.316	0.296	0.296	0.296	0.296	
		GRID_6_0 GW	1.833	1.832	1.832	1.832	1.832	1.785	1.782	1.781	1.78	1.78		GRID_6_0 GW	0.29	0.283	0.283	0.283	0.283	0.296	0.294	0.294	0.294	0.294	
HIN_E_pe ak	HIC_H_lo w	GRID_4_0 GW	3.353	3.282	3.466	3.626	3.77	1.598	1.56	1.48	1.357	1.262	HIC_H_lo w	GRID_4_0 GW	3.339	2.832	1.96	1.494	1.17	1.458	1.173	0.691	0.46	0.338	
		GRID_4_5 GW	2.696	2.599	2.607	2.654	2.651	1.532	1.5	1.41	1.274	1.184		GRID_4_5 GW	2.448	1.991	1.275	0.909	0.727	1.106	0.855	0.466	0.314	0.237	
		GRID_5_0 GW	2.274	2.197	2.168	2.151	2.13	1.474	1.448	1.352	1.178	1.076		GRID_5_0 GW	1.718	1.324	0.772	0.533	0.39	0.814	0.605	0.318	0.23	0.192	
		GRID_5_5 GW	2.033	1.976	1.944	1.901	1.885	1.428	1.404	1.275	1.123	1.059		GRID_5_5 GW	1.154	0.829	0.431	0.283	0.209	0.579	0.417	0.233	0.184	0.177	
		GRID_6_0 GW	1.896	1.856	1.829	1.799	1.776	1.383	1.356	1.241	1.109	1.109		GRID_6_0 GW	0.755	0.502	0.239	0.174	0.16	0.418	0.289	0.183	0.172	0.172	
	HIC_H_pe ak	GRID_4_0 GW	3.411	3.34	3.529	3.676	3.822	1.912	1.898	1.871	1.844	1.831	HIC_H_pe ak	GRID_4_0 GW	2.497	2.139	1.523	1.194	0.966	1.162	0.961	0.621	0.458	0.372	
		GRID_4_5 GW	2.763	2.669	2.676	2.724	2.721	1.877	1.863	1.842	1.818	1.806		GRID_4_5 GW	1.868	1.545	1.04	0.782	0.653	0.914	0.736	0.462	0.355	0.301	
		GRID_5_0 GW	2.35	2.274	2.247	2.231	2.207	1.848	1.837	1.818	1.795	1.784		GRID_5_0 GW	1.352	1.075	0.684	0.516	0.415	0.708	0.56	0.357	0.296	0.269	
		GRID_5_5 GW	2.115	2.059	2.027	1.988	1.972	1.826	1.817	1.797	1.78	1.771		GRID_5_5 GW	0.955	0.725	0.444	0.34	0.287	0.541	0.427	0.298	0.263	0.258	
		GRID_6_0 GW	1.982	1.943	1.917	1.89	1.868	1.812	1.805	1.787	1.773	1.773		GRID_6_0 GW	0.673	0.494	0.309	0.263	0.253	0.428	0.337	0.262	0.254	0.254	

			Configurations Installed Capacity Electrolysis										Configurations Installed Capacity NH3 Cracking												
			Wind_low					Wind_peak								Wind_low					Wind_peak				
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW
HIN_E_lo w	HIC_H_lo w	GRID_4_0 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.603	9.603	9.603	HIC_H_lo w	GRID_4_0 GW	3.6	3.6	3.6	3.6	3.6	1.16	1.14	0.99	0.95	0.95	
		GRID_4_5 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.603	9.603	9.603		GRID_4_5 GW	3.6	3.6	3.6	3.6	3.6	1.14	1.12	0.97	0.95	0.95	
		GRID_5_0 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.593	9.593		GRID_5_0 GW	3.6	3.6	3.6	3.6	3.6	1.13	1.1	0.99	0.98	0.98	
		GRID_5_5 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.593	9.593		GRID_5_5 GW	3.6	3.6	3.6	3.6	3.6	1.12	1.1	1.06	1.06	1.06	
		GRID_6_0 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.593	9.593		GRID_6_0 GW	3.6	3.6	3.6	3.6	3.6	1.12	1.1	1.1	1.1	1.1	
	HIC_H_pe ak	GRID_4_0 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613	HIC_H_pe ak	GRID_4_0 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42
		GRID_4_5 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_4_5 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
		GRID_5_0 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_5_0 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
		GRID_5_5 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_5_5 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
		GRID_6_0 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_6_0 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
HIN_E_pe ak	HIC_H_lo w	GRID_4_0 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.603	9.603	HIC_H_lo w	GRID_4_0 GW	3.6	3.6	3.6	3.6	3.6	1.42	1.42	1.4	1.37	1.37	
		GRID_4_5 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.603	9.603		GRID_4_5 GW	3.6	3.6	3.6	3.6	3.6	1.34	1.32	1.3	1.24	1.23	
		GRID_5_0 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.603	9.603		GRID_5_0 GW	3.6	3.6	3.6	3.6	3.6	1.27	1.26	1.23	1.15	1.13	
		GRID_5_5 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.603	9.603		GRID_5_5 GW	3.6	3.6	3.6	3.6	3.6	1.21	1.2	1.17	1.07	1.05	
		GRID_6_0 GW	3.666	3.666	3.666	3.666	3.666	9.593	9.593	9.593	9.603	9.603		GRID_6_0 GW	3.6	3.6	3.6	3.6	3.6	1.19	1.19	1.13	1.02	1.02	
	HIC_H_pe ak	GRID_4_0 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613	HIC_H_pe ak	GRID_4_0 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42
		GRID_4_5 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_4_5 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
		GRID_5_0 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_5_0 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
		GRID_5_5 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_5_5 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
		GRID_6_0 GW	3.666	3.666	3.666	3.666	3.666	9.613	9.613	9.613	9.613	9.613		GRID_6_0 GW	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	14.42	
			Configurations FLH Electrolysis										Configurations FLH NH3 Cracking												
			Wind_low					Wind_peak								Wind_low					Wind_peak				
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW
HIN_E_lo w	HIC_H_lo w	GRID_4_0 GW	5017	5048	5120	5187	5219	4535	4544	4579	4593	4593	HIC_H_lo w	GRID_4_0 GW	5201	5179	5128	5080	5057	1114	1082	973	912	912	
		GRID_4_5 GW	5109	5133	5207	5282	5282	4543	4551	4584	4591	4591		GRID_4_5 GW	5135	5118	5065	5012	5012	1084	1052	957	922	922	
		GRID_5_0 GW	5159	5176	5245	5281	5281	4548	4555	4586	4591	4591		GRID_5_0 GW	5100	5088	5039	5013	5013	1069	1043	953	930	930	
		GRID_5_5 GW	5187	5196	5225	5228	5228	4550	4556	4571	4571	4571		GRID_5_5 GW	5080	5074	5053	5050	5050	1061	1045	987	987	987	
		GRID_6_0 GW	5199	5199	5200	5200	5200	4551	4555	4557	4557	4557		GRID_6_0 GW	5072	5071	5071	5071	5071	1058	1048	1040	1040	1040	
	HIC_H_pe ak	GRID_4_0 GW	5017	5048	5120	5187	5219	5207	5234	5328	5365	5365	HIC_H_pe ak	GRID_4_0 GW	7888	7883	7870	7858	7852	6347	6334	6290	6273	6273	
		GRID_4_5 GW	5109	5133	5207	5282	5282	5220	5244	5335	5355	5355		GRID_4_5 GW	7872	7868	7854	7841	7841	6341	6329	6287	6277	6277	
		GRID_5_0 GW	5159	5176	5245	5281	5281	5227	5252	5328	5340	5340		GRID_5_0 GW	7863	7860	7848	7841	7841	6338	6326	6290	6285	6285	
		GRID_5_5 GW	5187	5196	5225	5228	5228	5231	5254	5295	5295	5295		GRID_5_5 GW	7858	7856	7851	7851	7851	6335	6325	6306	6306	6306	
		GRID_6_0 GW	5199	5199	5200	5200	5200	5233	5248	5251	5251	5251		GRID_6_0 GW	7856	7856	7856	7856	7856	6335	6328	6326	6326	6326	
HIN_E_pe ak	HIC_H_lo w	GRID_4_0 GW	3968	3992	3881	3802	3734	4471	4479	4499	4521	4532	HIC_H_lo w	GRID_4_0 GW	5950	5933	6013	6069	6118	1220	1185	1098	997	942	
		GRID_4_5 GW	4374	4433	4423	4394	4401	4494	4501	4523	4546	4557		GRID_4_5 GW	5661	5619	5625	5646	5641	1183	1154	1062	960	907	
		GRID_5_0 GW	4693	4753	4768	4800	4830	4512	4518	4539	4568	4579		GRID_5_0 GW	5432	5390	5379	5356	5335	1150	1126	1035	912	855	
		GRID_5_5 GW	4906	4953	4981	5058	5084	4526	4531	4556	4583	4590		GRID_5_5 GW	5280	5247	5227	5172	5153	1123	1102	990	886	851	
		GRID_6_0 GW	5037	5074	5098	5184	5217	4535	4540	4564	4590	4590		GRID_6_0 GW	5187	5161	5143	5082	5058	1093	1068	972	882	882	
	HIC_H_pe ak	GRID_4_0 GW	3968	3992	3881	3802	3734	5081	5100	5168	5242	5258	HIC_H_pe ak	GRID_4_0 GW	8076	8071	8091	8105	8117	6406	6397	6365	6331	6323	
		GRID_4_5 GW	4374	4433	4423	4394	4401	5116	5135	5202	5274	5295		GRID_4_5 GW	8003	7993	7994	7999	7998	6389	6380	6349	6316	6306	
		GRID_5_0 GW	4693	4753	4768	4800	4830	5146	5163	5227	5307	5327		GRID_5_0 GW	7946	7935	7933	7927	7922	6376	6367	6337	6300	6291	
		GRID_5_5 GW	4906	4953	4981	5058	5084	5167	5184	5251	5330	5349		GRID_5_5 GW	7908	7900	7895	7881	7876	6365	6358	6326	6289	6280	
		GRID_6_0 GW	5037	5074	5098	5184	5217	5183	5197	5265	5341	5341		GRID_6_0 GW	7885	7878	7874	7858	7853	6358	6351	6320	6284	6284	

			Configurations Installed Storage Capacity BESS										Configurations Installed Storage Capacity Salt Cavern													
			Wind_low					Wind_peak								Wind_low					Wind_peak					
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	
HIN_E_lo w	HIC_H_lo w	GRID_4_0 GW	0	5	20	35	50	0	5	20	29.99	29.99	HIC_H_lo w	HIC_H_lo w	GRID_4_0 GW	0	0	0	0	0	0	434.8	434.8	435.7	435.7	435.7
		GRID_4_5 GW	0	5	20	34.57	34.57	0	5	17.04	17.04	17.04			GRID_4_5 GW	0	0	0	0	0	0	434.8	434.8	435.7	435.7	435.7
		GRID_5_0 GW	0	5	16.08	16.08	16.08	0	5	11.64	11.64	11.64			GRID_5_0 GW	0	0	0	0	0	0	434.8	434.8	434.8	434.8	434.8
		GRID_5_5 GW	0	5	7.64	7.64	7.64	0	5	6.57	6.57	6.57			GRID_5_5 GW	0	0	0	0	0	0	434.8	434.8	434.8	434.8	434.8
		GRID_6_0 GW	0	2.42	2.42	2.42	2.42	0	2.08	2.08	2.08	2.08			GRID_6_0 GW	0	0	0	0	0	0	434.8	434.8	434.8	434.8	434.8
		GW													GW											
	HIC_H_pe ak	GRID_4_0 GW	0	5	20	35	50	0	5	20	29.99	29.99	HIC_H_pe ak	HIC_H_pe ak	GRID_4_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_4_5 GW	0	5	20	34.57	34.57	0	5	17.04	17.04	17.04			GRID_4_5 GW	0	0	0	0	0	0	0	0	0	0	
		GRID_5_0 GW	0	5	16.08	16.08	16.08	0	5	11.64	11.64	11.64			GRID_5_0 GW	0	0	0	0	0	0	0	0	0	0	
		GRID_5_5 GW	0	5	7.64	7.64	7.64	0	5	6.57	6.57	6.57			GRID_5_5 GW	0	0	0	0	0	0	0	0	0	0	
		GRID_6_0 GW	0	2.42	2.42	2.42	2.42	0	2.08	2.08	2.08	2.08			GRID_6_0 GW	0	0	0	0	0	0	0	0	0	0	
		GW													GW											
HIN_E_pe ak	HIC_H_lo w	GRID_4_0 GW	0	5	20	35	50	0	5	20	35	50	HIC_H_lo w	HIC_H_lo w	GRID_4_0 GW	0	0	0	0	0	0	434.8	434.8	434.8	435.7	435.7
		GRID_4_5 GW	0	5	20	35	50	0	5	20	35	50			GRID_4_5 GW	0	0	0	0	0	0	434.8	434.8	434.8	435.7	435.7
		GRID_5_0 GW	0	5	20	35	50	0	5	20	35	50			GRID_5_0 GW	0	0	0	0	0	0	434.8	434.8	434.8	435.7	435.7
		GRID_5_5 GW	0	5	20	35	50	0	5	20	35	50			GRID_5_5 GW	0	0	0	0	0	0	434.8	434.8	434.8	435.7	435.7
		GRID_6_0 GW	0	5	20	35	50	0	5	20	31.07	31.07			GRID_6_0 GW	0	0	0	0	0	0	434.8	434.8	434.8	435.7	435.7
		GW													GW											
	HIC_H_pe ak	GRID_4_0 GW	0	5	20	35	50	0	5	20	35	50	HIC_H_pe ak	HIC_H_pe ak	GRID_4_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_4_5 GW	0	5	20	35	50	0	5	20	35	50			GRID_4_5 GW	0	0	0	0	0	0	0	0	0	0	
		GRID_5_0 GW	0	5	20	35	50	0	5	20	35	50			GRID_5_0 GW	0	0	0	0	0	0	0	0	0	0	
		GRID_5_5 GW	0	5	20	35	50	0	5	20	35	50			GRID_5_5 GW	0	0	0	0	0	0	0	0	0	0	
		GRID_6_0 GW	0	5	20	35	50	0	5	20	31.07	31.07			GRID_6_0 GW	0	0	0	0	0	0	0	0	0	0	
		GW													GW											

			Configurations Cycle Rate BESS										Configurations Cycle Rate Salt Cavern													
			Wind_low					Wind_peak								Wind_low					Wind_peak					
			BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW				BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	BESS-- 0GW	BESS-- 5GW	BESS-- 20GW	BESS-- 35GW	BESS-- 50GW	
HIN_E_lo w	HIC_H_lo w	GRID_4_0 GW	0	395.9	271.7	161.9	124.6	0	380.4	285.8	234.5	234.5	HIC_H_lo w	HIC_H_lo w	GRID_4_0 GW	0	0	0	0	0	0	19.67	19.4	19.32	19.27	19.27
		GRID_4_5 GW	0	398.5	271	187.8	187.8	0	363.4	321.6	324.7	324.7			GRID_4_5 GW	0	0	0	0	0	0	19.65	19.41	19.34	19.42	19.42
		GRID_5_0 GW	0	404	359.2	366.5	366.5	0	374.9	375.5	380.9	380.9			GRID_5_0 GW	0	0	0	0	0	0	19.64	19.39	19.37	19.42	19.42
		GRID_5_5 GW	0	423.6	482.1	483.2	483.2	0	378.4	417.1	417.1	417.1			GRID_5_5 GW	0	0	0	0	0	0	19.63	19.39	19.36	19.36	19.36
		GRID_6_0 GW	0	501.4	541.4	541.4	541.4	0	438.1	450.2	450.2	450.2			GRID_6_0 GW	0	0	0	0	0	0	19.63	19.53	19.53	19.53	19.53
		GW													GW											
	HIC_H_pe ak	GRID_4_0 GW	0	395.9	271.7	161.9	124.6	0	434.6	366.2	308	308	HIC_H_pe ak	HIC_H_pe ak	GRID_4_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_4_5 GW	0	398.5	271	187.8	187.8	0	423.6	398.9	418.1	418.1			GRID_4_5 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_5_0 GW	0	404	359.2	366.5	366.5	0	429.4	466.1	473	473			GRID_5_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_5_5 GW	0	423.6	482.1	483.2	483.2	0	432.3	501.8	502	502			GRID_5_5 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_6_0 GW	0	501.4	541.4	541.4	541.4	0	507.5	541.7	541.7	541.7			GRID_6_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GW													GW											
HIN_E_pe ak	HIC_H_lo w	GRID_4_0 GW	0	264.9	153.6	101.4	78.2	0	397.3	335.2	266.3	169.6	HIC_H_lo w	HIC_H_lo w	GRID_4_0 GW	0	0	0	0	0	0	20.93	20.77	20.31	20.49	20.42
		GRID_4_5 GW	0	288.8	181.9	122.9	91.6	0	401.6	331.9	240.4	176.8			GRID_4_5 GW	0	0	0	0	0	0	20.86	20.74	20.3	20.47	20.36
		GRID_5_0 GW	0	335.6	220.7	148.1	111	0	411.1	302	235.7	186.3			GRID_5_0 GW	0	0	0	0	0	0	20.8	20.71	20.31	20.42	20.34
		GRID_5_5 GW	0	380.7	261	182.5	131.7	0	370.3	318.1	249.4	196			GRID_5_5 GW	0	0	0	0	0	0	20.78	20.7	20.27	20.4	20.29
		GRID_6_0 GW	0	402.7	278.9	191.7	148.2	0	397.5	334.6	284.4	284.4			GRID_6_0 GW	0	0	0	0	0	0	20.76	20.68	20.23	20.39	20.39
		GW													GW											
	HIC_H_pe ak	GRID_4_0 GW	0	264.9	153.6	101.4	78.2	0	426.3	374.8	308.8	208.1	HIC_H_pe ak	HIC_H_pe ak	GRID_4_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_4_5 GW	0	288.8	181.9	122.9	91.6	0	430.8	373.1	286.2	218.1			GRID_4_5 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_5_0 GW	0	335.6	220.7	148.1	111	0	440.9	351.9	293.6	228.3			GRID_5_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_5_5 GW	0	380.7	261	182.5	131.7	0	410.2	365.4	309	240.7			GRID_5_5 GW	0	0	0	0	0	0	0	0	0	0	0
		GRID_6_0 GW	0	402.7	278.9	191.7	148.2	0	427.6	376.6	343.5	343.5			GRID_6_0 GW	0	0	0	0	0	0	0	0	0	0	0
		GW													GW											

4. Experiment 4: Fixed H2 Import

		Scenario space EENS								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	47800	39100	30300	21500	12700	4040	301	301	301
	Wind_mid	24900	16200	7600	1950	53	53	53	53	53
	Wind_peak	5960	1370	19	19	19	19	19	19	19
		Scenario space LOLE								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	8784	8784	8784	8521	6476	2383	225	224	183
	Wind_mid	7018	4879	2275	849	44	41	43	41	35
	Wind_peak	1396	439	13	14	14	14	13	14	14
		Scenario space U Rate E								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	0.249	0.249	0.249	0.249	0.249	0.248	0.169	0.029	0
	Wind_mid	0.607	0.606	0.604	0.555	0.447	0.308	0.169	0.029	0
	Wind_peak	0.906	0.841	0.724	0.586	0.447	0.308	0.169	0.029	0
		Scenario space Avg. CO2								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	19.07	19.07	19.07	19.07	19.07	19.06	17.83	15.79	16.65
	Wind_mid	15.89	15.88	15.88	15.09	13.74	12.31	11.31	11.38	13.2
	Wind_peak	11.85	11.22	10.4	9.61	8.84	8.99	9.56	10.33	11.44
		Scenario space LCOHe								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	12.80	12.80	12.80	12.20	11.90	12.70	14.70	4.39	-196000000
	Wind_mid	11.00	11.00	11.40	11.80	13.10	11.50	9.00	-4.22	-284000000
	Wind_peak	11.20	11.60	12.50	11.70	10.60	9.28	7.65	-6.75	-318000000
		Scenario space LCOHi								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	0	8.724	8.724	8.724	8.724	8.724	8.724	8.724	8.724
	Wind_mid	0	8.724	8.724	8.724	8.724	8.724	8.724	8.724	8.724
	Wind_peak	0	8.724	8.724	8.724	8.724	8.724	8.724	8.724	8.724
		Scenario space LCOH Difference								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	12.8	4.04	4.05	3.46	3.2	4	5.99	-4.34	-196000000
	Wind_mid	11	2.3	2.67	3.02	4.39	2.77	0.274	-12.9	-284000000
	Wind_peak	11.2	2.87	3.74	2.97	1.88	0.56	-1.07	-15.5	-318000000
		Scenario space Avg. SC								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	33.06	27.03	21	14.96	8.94	2.98	0.42	0.41	0.42
	Wind_mid	17.34	11.37	5.43	1.56	0.26	0.25	0.24	0.24	0.25
	Wind_peak	4.32	1.17	0.25	0.24	0.23	0.22	0.22	0.22	0.23

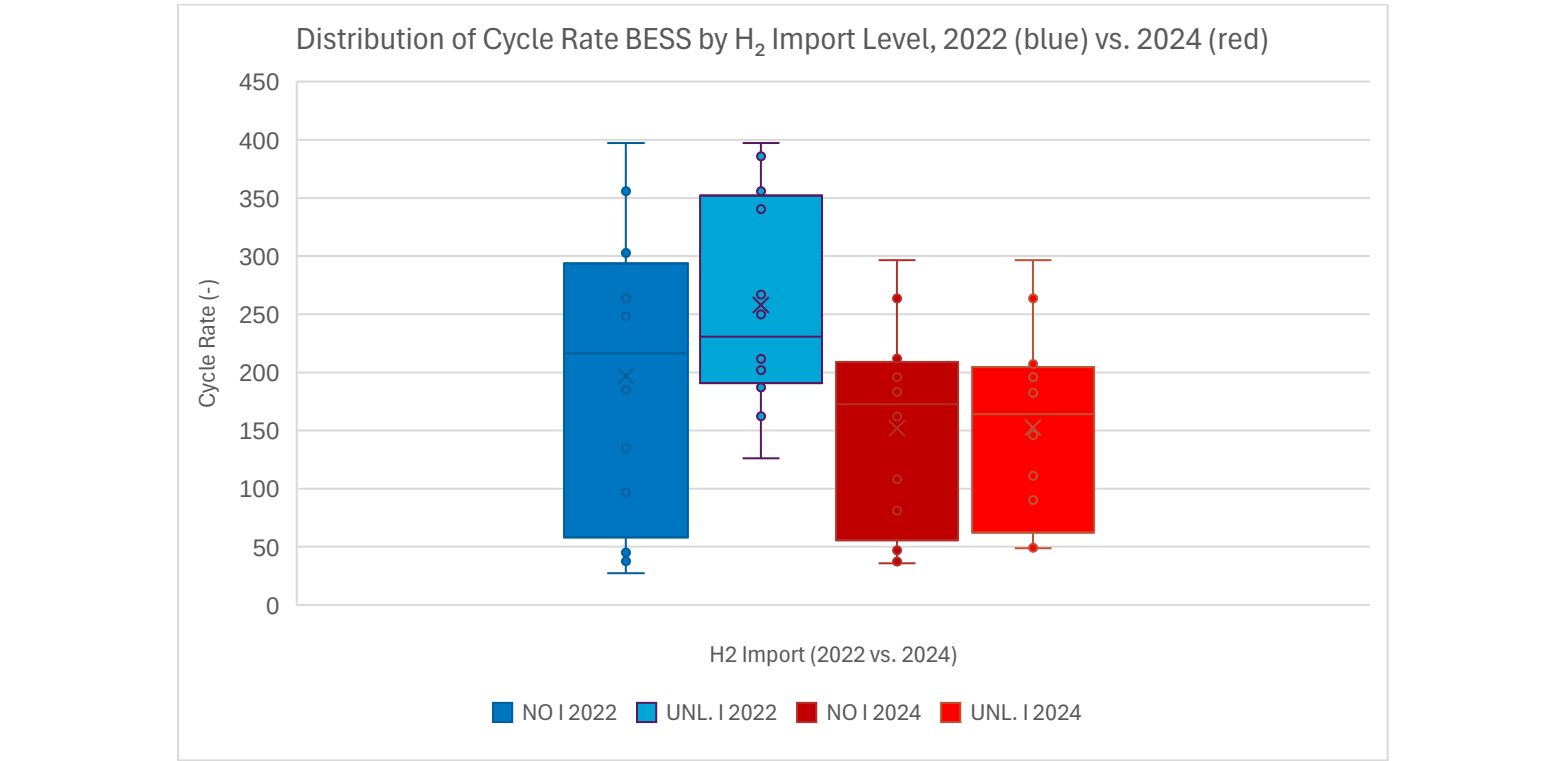
		Scenario space Installed Capacity Electrolysis								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	6.45	6.45	6.45	6	5.79	6.41	5.82	0.88	0
	Wind_mid	11.59	11.59	12.26	12.19	12.19	7.38	3.36	0.53	0
	Wind_peak	17.97	17.84	17.74	13.37	9.05	5.42	2.82	0.47	0
		Scenario space Installed Capacity NH3 Cracking								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	0	1	2	3	4	5	6	7	8
	Wind_mid	0	1	2	3	4	5	6	7	8
	Wind_peak	0	1	2	3	4	5	6	7	8
		Scenario space FLH Electrolysis								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	3485	3485	3485	3750	3882	3499	2626	3006	0
	Wind_mid	4727	4721	4454	4120	3316	3776	4534	4974	0
	Wind_peak	4568	4270	3696	3968	4469	5127	5401	5654	0
		Scenario space FLH NH3 Cracking								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	0	8784	8784	8784	8784	8784	8784	8784	8784
	Wind_mid	0	8784	8784	8784	8784	8784	8784	8784	8784
	Wind_peak	0	8784	8784	8784	8784	8784	8784	8784	8784
		Scenario space Installed Storage Capacity BESS								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	50	50	50	50	50	50	50	50	50
	Wind_mid	50	50	50	50	50	50	50	50	50
	Wind_peak	50	50	50	50	50	50	50	50	50
		Scenario space Installed Storage Capacity Salt Cavern								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	0	0	0	0	119	414	399	57	0
	Wind_mid	129	267	770	1250	760	413	160	23	0
	Wind_peak	1250	1250	1084	719	437	222	107	16	0
		Scenario space Cycle Rate BESS								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	35.7	35.7	35.7	35.7	35.7	36.1	111.3	145.6	147.5
	Wind_mid	22.9	23.3	23.1	45.1	104.4	128.6	135.7	140.9	142.6
	Wind_peak	33.1	45.3	113.1	128.7	136.6	141.5	145	146.9	147.5
		Scenario space Cycle Rate Salt Cavern								
		NH3_0GW	NH3_1GW	NH3_2GW	NH3_3GW	NH3_4GW	NH3_5GW	NH3_6GW	NH3_7GW	NH3_8GW
Scenario space	Wind_low	0	0	0	0	4.22	7.86	12.3	18.84	0
	Wind_mid	4.55	10.35	8.36	7.47	12.58	18.83	24.69	27.25	0
	Wind_peak	9.55	11.06	12.83	18.03	21.76	25.11	25.98	26.82	0

5. Experiment 5: Extreme H2 Supply

Scenario space EENS										Scenario space LOLE											
2022										2024											
NH3_0GW										NH3_16GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
NH3_16GW										NH3_0GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
PPA_req_0	GRID_EL_0	Wind_low	31805	126803	139	139	31966	126964	300	300	PPA_req_0	GRID_EL_0	Wind_low	8784	8784	91	90	8784	8784	216	219
		Wind_mid	31720	126718	54	54	31718	126716	52	52			Wind_mid	8784	8784	37	37	8784	8784	37	40
		Wind_peak	31701	126699	35	35	31685	126683	19	19			Wind_peak	8784	8784	18	17	8784	8784	15	15
	GRID_EL_mt	Wind_low	15898	110896	139	139	16921	111919	300	300		GRID_EL_mt	Wind_low	8784	8784	91	92	8784	8784	212	210
		Wind_mid	475	94762	54	54	805	94847	52	52			Wind_mid	271	8784	38	39	426	8784	40	37
PPA_req_m	GRID_EL_0	Wind_peak	35	79265	35	35	19	79068	19	19	PPA_req_m	GRID_EL_0	Wind_peak	18	8784	17	19	15	8784	16	13
		Wind_low	18571	113569	139	139	18647	113645	300	300			Wind_low	8784	8784	93	93	8784	8784	217	219
		Wind_mid	7181	102098	54	54	6569	101476	52	52			Wind_mid	3802	8784	39	36	3558	8784	42	40
	GRID_EL_mt	Wind_peak	196	90962	35	35	19	89880	19	19		GRID_EL_mt	Wind_peak	207	8784	17	18	14	8784	14	13
		Wind_low	14120	109109	139	139	16180	111176	300	300			Wind_low	6650	8784	92	93	7303	8784	221	187
		Wind_mid	54	86937	54	54	52	88264	52	52			Wind_mid	39	8784	40	37	41	8784	41	41
		Wind_peak	35	64798	35	35	19	65428	19	19			Wind_peak	18	8784	18	18	15	8784	14	16
Scenario space U Rate E										Scenario space Avg. CO2											
2022										2024											
NH3_0GW										NH3_16GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
NH3_16GW										NH3_0GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
PPA_req_0	GRID_EL_0	Wind_low	0	0	0	0	0	0	0	0	PPA_req_0	GRID_EL_0	Wind_low	15.46	21.75	15.17	21.54	15.29	21.29	13.97	20.35
		Wind_mid	0	0	0	0	0	0	0	0			Wind_mid	11.79	19.32	11.15	18.77	10.32	17.78	9.80	17.41
		Wind_peak	0	0	0	0	0	0	0	0			Wind_peak	9.49	17.58	9.30	17.49	8.48	16.48	8.46	16.46
	GRID_EL_mt	Wind_low	0.502	0.126	0.065	0.016	0.475	0.119	0.436	0.109		GRID_EL_mt	Wind_low	17.53	23.17	15.46	21.74	16.60	22.21	16.46	22.12
		Wind_mid	0.987	0.252	0.149	0.04	0.976	0.252	0.881	0.233			Wind_mid	13.07	20.09	11.41	18.93	12.12	19.06	11.71	18.82
PPA_req_m	GRID_EL_0	Wind_peak	1	0.374	0.237	0.063	1	0.376	0.992	0.351	PPA_req_m	GRID_EL_0	Wind_peak	9.16	17.28	9.19	17.38	7.58	16.12	7.59	15.76
		Wind_low	0.418	0.104	0.07	0.018	0.421	0.105	0.393	0.098			Wind_low	16.91	22.74	14.57	21.12	16.28	21.99	16.10	21.86
		Wind_mid	0.775	0.194	0.172	0.044	0.794	0.199	0.766	0.193			Wind_mid	11.66	19.11	9.80	17.84	10.73	18.07	10.61	17.99
	GRID_EL_mt	Wind_peak	0.995	0.282	0.327	0.086	1	0.291	0.97	0.284		GRID_EL_mt	Wind_peak	7.31	16.14	6.62	15.63	6.00	14.74	5.96	14.69
		Wind_low	0.559	0.14	0.084	0.021	0.498	0.125	0.471	0.118			Wind_low	17.74	23.31	14.64	21.17	16.76	22.33	16.57	22.19
		Wind_mid	1	0.314	0.206	0.061	1	0.304	0.955	0.289			Wind_mid	13.03	20.71	9.96	18.03	12.31	19.77	12.11	19.57
		Wind_peak	1	0.489	0.412	0.122	1	0.484	1	0.462			Wind_peak	8.37	18.13	7.16	16.09	7.87	17.24	7.87	17.08
Scenario space LCOHe										Scenario space LCOHI											
2022										2024											
NH3_0GW										NH3_16GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
NH3_16GW										NH3_0GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
PPA_req_0	GRID_EL_0	Wind_low	0	0	0	0	0	0	0	0	PPA_req_0	GRID_EL_0	Wind_low	0	0	8.72	8.72	0	0	8.72	8.72
		Wind_mid	0	0	0	0	0	0	0	0			Wind_mid	0	0	8.72	8.72	0	0	8.72	8.72
		Wind_peak	0	0	0	0	0	0	0	0			Wind_peak	0	0	8.72	8.72	0	0	8.72	8.72
	GRID_EL_mt	Wind_low	18.6	18.6	41.2	41.2	9.7	9.7	9.9	9.9		GRID_EL_mt	Wind_low	0	0	8.73	8.73	0	0	8.84	8.74
		Wind_mid	18.8	18.8	33.4	32.2	9.2	9.1	9.4	9.3			Wind_mid	0	0	8.75	8.73	0	0	9.45	8.77
PPA_req_m	GRID_EL_0	Wind_peak	18.1	18.9	31.4	29.9	10.2	9.1	10.3	9.1	PPA_req_m	GRID_EL_0	Wind_peak	0	0	8.76	8.73	0	0	12.94	8.8
		Wind_low	10.4	10.4	-17	-17	10.7	10.7	10.9	10.9			Wind_low	0	0	8.73	8.73	0	0	8.82	8.74
		Wind_mid	10.7	10.7	-11.3	-10.4	10.6	10.6	10.6	10.6			Wind_mid	0	0	8.75	8.73	0	0	9.08	8.76
	GRID_EL_mt	Wind_peak	9.6	10.7	-5.4	-4.1	11.1	10.6	11.2	10.6		GRID_EL_mt	Wind_peak	0	0	8.78	8.74	0	0	10.1	8.78
		Wind_low	13.7	13.9	-2.4	3.1	12.2	12.6	11.7	12.4			Wind_low	0	0	8.74	8.73	0	0	8.86	8.74
		Wind_mid	12.8	14.6	-2.4	6.5	11.5	11.2	11.5	11.1			Wind_mid	0	0	8.76	8.73	0	0	9.96	8.79
		Wind_peak	11.7	14.8	6.1	8.5	14.5	10.8	14.5	10.8			Wind_peak	0	0	8.79	8.74	0	0	0	8.85
Scenario space LCOH Difference										Scenario space Avg. SC											
2022										2024											
NH3_0GW										NH3_16GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
NH3_16GW										NH3_0GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
PPA_req_0	GRID_EL_0	Wind_low	0	0	-8.72	-8.72	0	0	-8.72	-8.72	PPA_req_0	GRID_EL_0	Wind_low	27.17	74.26	0.4	0.43	25.15	70.36	0.38	0.41
		Wind_mid	0	0	-8.72	-8.72	0	0	-8.72	-8.72			Wind_mid	27.11	74.22	0.34	0.38	24.96	70.22	0.19	0.27
		Wind_peak	0	0	-8.72	-8.72	0	0	-8.72	-8.72			Wind_peak	27.1	74.22	0.33	0.38	24.93	70.2	0.17	0.26
	GRID_EL_mt	Wind_low	18.6	18.6	32.47	32.47	9.7	9.7	1.06	1.16		GRID_EL_mt	Wind_low	13.74	65.01	0.42	0.44	13.38	62.05	0.38	0.41
		Wind_mid	18.8	18.8	24.65	23.47	9.2	9.1	-0.05	0.53			Wind_mid	0.76	55.64	0.37	0.4	0.78	52.62	0.19	0.28
PPA_req_m	GRID_EL_0	Wind_peak	18.1	18.9	22.64	21.17	10.2	9.1	-2.64	0.3	PPA_req_m	GRID_EL_0	Wind_peak	0.4	46.63	0.38	0.41	0.18	43.91	0.18	0.26
		Wind_low	10.4	10.4	-25.73	-25.73	10.7	10.7	2.08	2.16			Wind_low	15.97	66.54	0.43	0.44	14.74	63	0.39	0.41
		Wind_mid	10.7	10.7	-20.05	-19.13	10.6	10.6	1.52	1.84			Wind_mid	6.37	59.87	0.38	0.41	5.3	56.29	0.2	0.28
	GRID_EL_mt	Wind_peak	9.6	10.7	-14.18	-12.84	11.1	10.6	1.1	1.82		GRID_EL_mt	Wind_peak	0.48	53.39	0.37	0.4	0.19	49.89	0.19	0.27
		Wind_low	13.7	13.9	-11.14	-5.63	12.2	12.6	2.84	3.66			Wind_low	12.23	63.96	0.44	0.45	12.82	61.65	0.4	0.42
		Wind_mid	12.8	14.6	-11.16	-2.23	11.5	11.2	1.54	2.31			Wind_mid	0.38	51.06	0.39	0.42	0.22	49	0.22	0.29
		Wind_peak	11.7	14.8	-2.69	-0.24	14.5	10.8	14.5	1.95			Wind_peak	0.41	38.19	0.41	0.43	0.23	36.4	0.23	0.28
Scenario space Installed Capacity Electrolysis										Scenario space Installed Capacity NH3 Cracking											
2022										2024											
NH3_0GW										NH3_16GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
NH3_16GW										NH3_0GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
PPA_req_0	GRID_EL_0	Wind_low	0	0	0	0	0	0	0	0	PPA_req_0	GRID_EL_0	Wind_low	0	0	3.6	14.42	0	0	3.6	14.42
		Wind_mid	0	0	0	0	0	0	0	0			Wind_mid	0	0	3.6	14.42	0	0	3.6	14.42
		Wind_peak	0	0	0	0	0	0	0	0			Wind_peak	0	0	3.6	14.42	0	0	3.6	14.42
	GRID_EL_mt	Wind_low	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7		GRID_EL_mt	Wind_low	0	0	3.6	14.42	0	0	3.6	14.42
		Wind_mid	6.7	6.7	6.57	6.7	6.7	6.7	6.7	6.7			Wind_mid	0	0	3.6	14.42	0	0	3.6	14.42
PPA_req_m	GRID_EL_0	Wind_peak	9.7	9.7	9.7	9.7	9.7	9.7	9.7	9.7	PPA_req_m	GRID_EL_0	Wind_peak	0	0	3.57	14.42	0	0	2.52	14.42
		Wind_low	3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67			Wind_low	0	0	3.4	14.42	0	0	0.87	14.42
		Wind_mid	6.64	6.64	6.48	6.64	6.64	6.64	6.63	6.64			Wind_mid	0	0	3.6	14.42	0	0	3.6	14.42
	GRID_EL_mt	Wind_peak	9.61	9.61	9.31	9.61	9.61	9.61	9.6	9.61		GRID_EL_mt	Wind_peak	0	0	3.56	14.42	0	0	2.87	14.42
		Wind_low	6.54	6.81	5.13	5.87	5.71	6.03	5.13	5.67			Wind_low	0	0	3.38	14.42	0	0	1.13	14.42
		Wind_mid	11.33	12.72	8.54	11.59	10.91	11.79	10.45	11.51			Wind_mid	0	0	3.6	14.42	0	0	3.6	14.42
		Wind_peak	17.63	18.63	15.62	17.59	16.84	17.55	16.84	17.42			Wind_peak	0	0	3.49	14.42	0	0	1.53	14.42
													Wind_peak	0	0	3.06	14.42	0	0	0	14.42
Scenario space FLH Electrolysis										Scenario space FLH NH3 Cracking											
2022										2024											
NH3_0GW										NH3_16GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
NH3_16GW										NH3_0GW											
HIC_H_low HIC_H_peak										HIC_H_low HIC_H_peak											
PPA_req_0	GRID_EL_0	Wind_low	0	0	0	0	0	0	0	0	PPA_req_0	GRID_EL_0	Wind_low	0	0	8784	8784	0	0	8784	8784
		Wind_mid	0	0	0	0	0	0	0	0			Wind_mid	0	0	8784	8784	0	0	8784	8784
		Wind_peak	0	0	0	0	0	0	0	0			Wind_peak	0	0	8784	8784	0	0	8784	8784
	GRID_EL_mt	Wind_low	6123	6123	796	796	5792	5792	5315	5315		GRID_EL_mt	Wind_low	0	0	8210	8641	0	0	4954	7827
		Wind_mid	6667	6793	1023	1071	6596	6775	5953	6272			Wind_mid	0	0	7548	8435	0	0	1497	6738
PPA_req_m	GRID_EL_0	Wind_peak	4686	6965	1102	1174	4687	6992	4649	6524	PPA_req_m	GRID_EL_0	Wind_peak	0	0	7120	8230	0	0	299	5703
		Wind_low	5140	5140	866	866	5174	5174	4830												

			Scenario space Installed Storage Capacity BESS											Scenario space Installed Storage Capacity Salt Cavern									
			2022				2024							2022				2024					
			NH3_0GW		NH3_16GW		NH3_0GW		NH3_16GW					NH3_0GW		NH3_16GW		NH3_0GW		NH3_16GW			
			HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak				HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak		
PPA_req_0	GRID_EL_0	Wind_low	50	50	50	50	50	50	50	50	PPA_req_0	GRID_EL_0	Wind_low	0	0	0	0	0	0	0	0	0	
		Wind_mid	50	50	50	50	50	50	50	50			50	0	0	0	0	0	0	0	0	0	
		Wind_peak	50	50	50	50	50	50	50	50			50	0	0	0	0	0	0	0	0	0	
		Wind_low	50	50	50	50	50	50	50	50			50	0	0	0	0	0	0	0	0	0	
PPA_req_m	GRID_EL_ml	Wind_mid	50	50	50	50	50	50	50	50	PPA_req_m	GRID_EL_ml	Wind_mid	1250	0	109	0	1250	0	229	0	229	0
		Wind_peak	50	50	50	50	50	50	50	50			1250	0	445	0	561	0	445	0	445	0	
		Wind_low	50	50	50	50	50	50	50	50			0	0	0	0	0	0	0	0	0	0	
		Wind_low	50	50	50	50	50	50	50	50			0	0	0	0	0	0	0	0	0	0	
PPA_req_m	GRID_EL_0	Wind_low	50	50	50	50	50	50	50	50	PPA_req_m	GRID_EL_0	Wind_low	286	0	131	0	227	0	146	0	146	0
		Wind_mid	50	50	50	50	50	50	50	50			1250	0	405	0	898	0	436	0	436	0	
		Wind_peak	50	50	50	50	50	50	50	50			137	0	0	0	56	0	0	0	0	0	
		Wind_low	50	50	50	50	50	50	50	50			1250	0	288	0	1028	0	519	0	519	0	
PPA_req_m	GRID_EL_ml	Wind_mid	50	50	50	50	50	50	50	50	PPA_req_m	GRID_EL_ml	Wind_mid	1250	0	959	0	1110	0	1110	0	1110	0
		Wind_peak	50	45.85	50	50	50	49.85	50	50			1250	0	959	0	1110	0	1110	0	1110	0	

			Scenario space Cycle Rate BESS											Scenario space Cycle Rate Salt Cavern									
			2022				2024							2022				2024					
			NH3_0GW		NH3_16GW		NH3_0GW		NH3_16GW					NH3_0GW		NH3_16GW		NH3_0GW		NH3_16GW			
			HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak				HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak	HIC_H_low	HIC_H_peak		
PPA_req_0	GRID_EL_0	Wind_low	266.8	266.8	266.8	266.8	196	196	195.9	195.9	PPA_req_0	GRID_EL_0	Wind_low	0	0	0	0	0	0	0	0	0	
		Wind_mid	355.9	355.9	355.9	355.9	263.7	263.7	263.7	263.7			0	0	0	0	0	0	0	0	0	0	
		Wind_peak	397.2	397.2	397.2	397.2	296.4	296.4	296.5	296.5			0	0	0	0	0	0	0	0	0	0	
		Wind_low	96.8	96.8	249.8	249.8	81	81	90.2	90.2			0	0	0	0	0	0	0	0	0	0	
PPA_req_m	GRID_EL_ml	Wind_mid	186.6	182.9	342	338.7	162.2	161.7	144.4	147.5	PPA_req_m	GRID_EL_ml	Wind_mid	4.59	0	5.48	0	4.62	0	22.59	0	22.59	0
		Wind_peak	283.3	244.2	385.8	385.9	184.1	216.1	185.5	190.2			9.8	0	6.99	0	22.58	0	28.28	0	28.28	0	
		Wind_low	134.8	134.8	208.9	208.9	108	108	111	111			0	0	0	0	0	0	0	0	0	0	
		Wind_low	248.3	248.3	211.5	211.6	182.7	183.7	181.7	183.2			7.92	0	5.52	0	10.6	0	15.95	0	15.95	0	
PPA_req_m	GRID_EL_0	Wind_peak	292.5	313.1	159.9	164.7	194.2	229.5	186.3	228.3	PPA_req_m	GRID_EL_0	Wind_peak	6.97	0	6.66	0	10.29	0	20.34	0	20.34	0
		Wind_low	27.3	27.2	202.4	201.7	35.7	35.7	50.5	47.9			3.44	0	0	0	1.75	0	0	0	0	0	
		Wind_mid	58.7	16.3	196.6	177.7	52	22.9	61.1	36.6			9.24	0	6.52	0	11.07	0	20.73	0	20.73	0	
		Wind_peak	77.3	12.9	130.8	121.3	77.1	17.1	77.1	28.4			13.35	0	6.33	0	15.5	0	15.5	0	15.5	0	



- Findings:
- BESS capacity is always optimised to the maximum (50 GWhe) in all scenarios (except 1, which is ~46 GWhe).
 - o The average number of BESS cycles is significantly higher in 2022 (~228 cycles) compared to 2024 (~152 cycles), mainly due to higher market volatility in 2022.
 - BESS cycling increases when H₂ import capacity is unlimited, since more electricity remains available for storage instead of being converted directly to hydrogen.
 - Hydrogen storage only plays a relevant role during low hydrogen demand scenarios, similar to Experiment 4, as only then hydrogen oversupply occurs.
 - LCOH_{electrolysis} is strongly linked to electrolyser FLHs and inversely related to BESS cycle rates:
 - o Less electricity converted to hydrogen means more electricity available for storage, allowing the BESS to operate more efficiently.

6. Additional Experiment: Grid Fees

This experiment explores how different grid tariff structures (fixed vs. variable) affect the competitiveness of electrolyzers. It investigates whether tariff reforms (under 36 different scenarios) could incentivise domestic hydrogen production and reduce the LCOH_{electrolysis}.

Key findings:

- Grid fees have only a limited impact on LCOH_{electrolysis}, leading to modest cost reductions—approximately €0.3/kg per 50% reduction in fixed fees and €0.4/kg per 50% reduction in variable fees—rather than transformative changes.
- Although grid tariffs are frequently cited in reports and policy discussions, this model indicates they do not substantially alter the economic viability of electrolyzers.

		Configurations EENS						Configurations LOLE			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	300.7	19.4	300.7	19.4	vGF_EL_low	fGF_EL_low	222	15	216	15
	fGF_EL_ml	300.7	19.4	300.7	19.4		fGF_EL_ml	222	15	216	15
	fGF_EL_mp	300.7	19.4	300.7	19.4		fGF_EL_mp	222	15	216	15
vGF_EL_ml	fGF_EL_low	300.7	19.4	300.7	19.4	vGF_EL_ml	fGF_EL_low	217	14	219	13
	fGF_EL_ml	300.7	19.4	300.7	19.4		fGF_EL_ml	217	14	219	13
	fGF_EL_mp	300.7	19.4	300.7	19.4		fGF_EL_mp	217	14	219	13
vGF_EL_mp	fGF_EL_low	300.7	19.4	300.7	19.4	vGF_EL_mp	fGF_EL_low	220	14	229	13
	fGF_EL_ml	300.7	19.4	300.7	19.4		fGF_EL_ml	220	14	229	13
	fGF_EL_mp	300.7	19.4	300.7	19.4		fGF_EL_mp	220	14	229	13
		Configurations U Rate E						Configurations Avg. CO2			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	0.4	0.972	0.1	0.286	vGF_EL_low	fGF_EL_low	16.15	5.97	21.9	14.7
	fGF_EL_ml	0.4	0.972	0.1	0.286		fGF_EL_ml	16.15	5.97	21.9	14.7
	fGF_EL_mp	0.4	0.972	0.1	0.286		fGF_EL_mp	16.15	5.97	21.9	14.7
vGF_EL_ml	fGF_EL_low	0.393	0.97	0.098	0.284	vGF_EL_ml	fGF_EL_low	16.1	5.96	21.86	14.69
	fGF_EL_ml	0.393	0.97	0.098	0.284		fGF_EL_ml	16.1	5.96	21.86	14.69
	fGF_EL_mp	0.393	0.97	0.098	0.284		fGF_EL_mp	16.1	5.96	21.86	14.69
vGF_EL_mp	fGF_EL_low	0.383	0.964	0.096	0.28	vGF_EL_mp	fGF_EL_low	16.04	5.94	21.81	14.67
	fGF_EL_ml	0.383	0.964	0.096	0.28		fGF_EL_ml	16.04	5.94	21.81	14.67
	fGF_EL_mp	0.383	0.964	0.096	0.28		fGF_EL_mp	16.04	5.94	21.81	14.67
		Configurations LCOHe						Configurations LCOHi			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	10.2	10.47	10.21	9.89	vGF_EL_low	fGF_EL_low	8.82	9.97	8.74	8.78
	fGF_EL_ml	10.52	10.8	10.52	10.17		fGF_EL_ml	8.82	9.97	8.74	8.78
	fGF_EL_mp	10.83	11.14	10.83	10.46		fGF_EL_mp	8.82	9.97	8.74	8.78
vGF_EL_ml	fGF_EL_low	10.63	10.84	10.63	10.28	vGF_EL_ml	fGF_EL_low	8.82	10.1	8.74	8.78
	fGF_EL_ml	10.95	11.18	10.95	10.57		fGF_EL_ml	8.82	10.1	8.74	8.78
	fGF_EL_mp	11.27	11.51	11.27	10.86		fGF_EL_mp	8.82	10.1	8.74	8.78
vGF_EL_mp	fGF_EL_low	11.08	11.21	11.08	10.68	vGF_EL_mp	fGF_EL_low	8.82	10.27	8.74	8.78
	fGF_EL_ml	11.41	11.55	11.41	10.97		fGF_EL_ml	8.82	10.27	8.74	8.78
	fGF_EL_mp	11.73	11.89	11.73	11.27		fGF_EL_mp	8.82	10.27	8.74	8.78
		Configurations LCOH Difference						Configurations Avg. SC			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	1.381	0.49	1.465	1.103	vGF_EL_low	fGF_EL_low	0.387	0.187	0.413	0.265
	fGF_EL_ml	1.695	0.827	1.778	1.391		fGF_EL_ml	0.388	0.189	0.414	0.266
	fGF_EL_mp	2.009	1.163	2.092	1.679		fGF_EL_mp	0.389	0.192	0.414	0.268
vGF_EL_ml	fGF_EL_low	1.81	0.739	1.888	1.494	vGF_EL_ml	fGF_EL_low	0.389	0.189	0.414	0.267
	fGF_EL_ml	2.13	1.076	2.207	1.784		fGF_EL_ml	0.39	0.192	0.415	0.269
	fGF_EL_mp	2.449	1.413	2.527	2.074		fGF_EL_mp	0.391	0.194	0.415	0.271
vGF_EL_mp	fGF_EL_low	2.261	0.948	2.338	1.896	vGF_EL_mp	fGF_EL_low	0.39	0.192	0.415	0.27
	fGF_EL_ml	2.589	1.287	2.666	2.19		fGF_EL_ml	0.391	0.195	0.416	0.272
	fGF_EL_mp	2.917	1.626	2.994	2.484		fGF_EL_mp	0.392	0.197	0.417	0.273

		Configurations Installed Capacity Electrolysis						Configurations Installed Capacity NH3			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	2.574	6.742	2.574	6.749	vGF_EL_low	fGF_EL_low	3.6	0.97	14.42	14.42
	fGF_EL_ml	2.574	6.742	2.574	6.749		fGF_EL_ml	3.6	0.97	14.42	14.42
	fGF_EL_mp	2.574	6.742	2.574	6.749		fGF_EL_mp	3.6	0.97	14.42	14.42
vGF_EL_ml	fGF_EL_low	2.574	6.742	2.574	6.749	vGF_EL_ml	fGF_EL_low	3.6	1.13	14.42	14.42
	fGF_EL_ml	2.574	6.742	2.574	6.749		fGF_EL_ml	3.6	1.13	14.42	14.42
	fGF_EL_mp	2.574	6.742	2.574	6.749		fGF_EL_mp	3.6	1.13	14.42	14.42
vGF_EL_mp	fGF_EL_low	2.574	6.735	2.574	6.749	vGF_EL_mp	fGF_EL_low	3.6	1.48	14.42	14.42
	fGF_EL_ml	2.574	6.735	2.574	6.749		fGF_EL_ml	3.6	1.48	14.42	14.42
	fGF_EL_mp	2.574	6.735	2.574	6.749		fGF_EL_mp	3.6	1.48	14.42	14.42
		Configurations FLH Electrolysis						Configurations FLH NH3 Cracking			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	4921	4589	4921	5365	vGF_EL_low	fGF_EL_low	5269	932	7905	6272
	fGF_EL_ml	4921	4589	4921	5365		fGF_EL_ml	5269	932	7905	6272
	fGF_EL_mp	4921	4589	4921	5365		fGF_EL_mp	5269	932	7905	6272
vGF_EL_ml	fGF_EL_low	4829	4579	4829	5326	vGF_EL_ml	fGF_EL_low	5334	855	7921	6290
	fGF_EL_ml	4829	4579	4829	5326		fGF_EL_ml	5334	855	7921	6290
	fGF_EL_mp	4829	4579	4829	5326		fGF_EL_mp	5334	855	7921	6290
vGF_EL_mp	fGF_EL_low	4704	4558	4704	5257	vGF_EL_mp	fGF_EL_low	5424	771	7944	6323
	fGF_EL_ml	4704	4558	4704	5257		fGF_EL_ml	5424	771	7944	6323
	fGF_EL_mp	4704	4558	4704	5257		fGF_EL_mp	5424	771	7944	6323
		Configurations Installed Storage Capacity						Configurations Installed Storage Capacity			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	50	50	50	50	vGF_EL_low	fGF_EL_low	0	435.7	0	0
	fGF_EL_ml	50	50	50	50		fGF_EL_ml	0	435.7	0	0
	fGF_EL_mp	50	50	50	50		fGF_EL_mp	0	435.7	0	0
vGF_EL_ml	fGF_EL_low	50	50	50	50	vGF_EL_ml	fGF_EL_low	0	435.7	0	0
	fGF_EL_ml	50	50	50	50		fGF_EL_ml	0	435.7	0	0
	fGF_EL_mp	50	50	50	50		fGF_EL_mp	0	435.7	0	0
vGF_EL_mp	fGF_EL_low	50	50	50	50	vGF_EL_mp	fGF_EL_low	0	434.8	0	0
	fGF_EL_ml	50	50	50	50		fGF_EL_ml	0	434.8	0	0
	fGF_EL_mp	50	50	50	50		fGF_EL_mp	0	434.8	0	0
		Configurations Cycle Rate BESS						Configurations Cycle Rate Salt Cavern			
		HIC_H_low		HIC_H_peak				HIC_H_low		HIC_H_peak	
		Wind_low	Wind_peak	Wind_low	Wind_peak			Wind_low	Wind_peak	Wind_low	Wind_peak
vGF_EL_low	fGF_EL_low	110.7	186.4	110.7	230.1	vGF_EL_low	fGF_EL_low	0	20.38	0	0
	fGF_EL_ml	110.7	186.4	110.7	230.1		fGF_EL_ml	0	20.38	0	0
	fGF_EL_mp	110.7	186.4	110.7	230.1		fGF_EL_mp	0	20.38	0	0
vGF_EL_ml	fGF_EL_low	111	186.3	111	228.3	vGF_EL_ml	fGF_EL_low	0	20.34	0	0
	fGF_EL_ml	111	186.3	111	228.3		fGF_EL_ml	0	20.34	0	0
	fGF_EL_mp	111	186.3	111	228.3		fGF_EL_mp	0	20.34	0	0
vGF_EL_mp	fGF_EL_low	111.6	185	111.6	225.4	vGF_EL_mp	fGF_EL_low	0	20.35	0	0
	fGF_EL_ml	111.6	185	111.6	225.4		fGF_EL_ml	0	20.35	0	0
	fGF_EL_mp	111.6	185	111.6	225.4		fGF_EL_mp	0	20.35	0	0

