



Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Master thesis

Maximilian Riedl

RFNBO Ammonia Production: Integrating Techno-Economic Feasibility and REDII Compliance in a Computational Framework

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Renewable Energy Systems - Environmental and Process Engineering
Department of Environmental Engineering and Process Engineering
Faculty of Life Science
Hamburg University of Applied Sciences

In cooperation with
Hy2gen AG
Klingholzstraße 7
65189 Wiesbaden

1st Supervisor: Prof. Dr. Hans Schäfers (HAW Hamburg)
2nd Supervisor: Tobias Janning, M. Sc. (Hy2gen AG)

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Abstract

This master's thesis investigates the feasibility of producing ammonia as a renewable fuel of non-biological origin (RFNBO) in line with the EU Renewable Energy Directive (RED II) and its Delegated Regulations (EU) 2023/1184 and 2023/1185. A computational framework was developed to assess the techno-economic performance of Power-to-Ammonia (P2A) systems under strict regulatory constraints, including hourly correlation between renewable electricity use and generation, and a GHG emissions threshold of 28.2 gCO₂eq/MJ fuel. The model simulates hourly mass and energy balances for fixed system configurations, comprising PV and wind power, battery and hydrogen storage, electrolysis, and the Haber-Bosch synthesis loop. Sensitivity analyses on renewable supply and storage integration show that high-yield wind assets significantly reduce ammonia production costs, while battery storage enhances HB process stability by minimizing shutdowns. Though economically less attractive, battery systems complement hydrogen storage by improving operational continuity. The model enables GHG tracking and regulatory compliance assessment, offering a transparent, rule-based alternative to optimization tools. The thesis concludes that RFNBO-compliant ammonia production is technically and economically viable under specific design conditions, supporting future green ammonia deployment in decarbonization strategies.

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List of Abbreviations

aBioF.....	Advanced Biofuel
AEL	Alkaline Electrolysis
ASU.....	Air Separation Unit
ATB.....	Annual Technology Baseline
BAT	Best Available Technology
BESS	Battery Energy Storage System
BNetzA.....	Bundesnetzagentur
CapEx	Capital Expenditure
CBAM.....	Carbon Border Adjustment Mechanism
CCUS.....	Carbon Capture, Utilization, and Storage
CI	Carbon Intensity
COD	Commercial Operation Dates
DA.....	Delegated Act
DoD.....	Depth of Discharge
EEA.....	European Economic Area
EEG	Erneuerbare-Energien-Gesetz
EL	Electrolyzer
EnWG	Energiewirtschaftsgesetz
EU ETS	EU Emissions Trading System
FID	Final Investment Decision
FIFO.....	"First-In, First-Out" Approach
FLH	Full Load Hours
GATT	General Agreement on Tariffs and Trade
GHG.....	Greenhouse Gas
GoO	Guarantee of Origin
GWP	Global Warming Potential
HB.....	Haber-Bosch Process
HHV	Higher Heating Value
IDE.....	Integrated Development Environment
IRR.....	Internal Rate of Return

List of Abbreviations

JRC	Joint Research Centre
LCOA	Levelized Cost of Ammonia
LCOE	Levelized Cost of Electricity
LHV	Lower Heating Value
LRF	Linear Reduction Factor
MILP	Mixed-Integer Linear Programming
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
OpEx	Operational Expenditure
P2A	Power-to-Ammonia
PEMEL	Proton Exchange Membrane Electrolysis
PLO	Part Load Operation
PoS	Proof of Sustainability
PPA	Power Purchase Agreement
PtX	Power-to-X
PV	Photovoltaic
RE	Renewable Energy
REDII	Revised renewable energy directive (EU) 2018/2001
RES	Renewable Electricity Source
RFNBO	Renewable Fuel of non-Biological Origin
SAO	Storage Assisted Operation
SDO	Shutdown Operation
SMR	Steam Methane Reforming
SO	Surplus Operation
SOC	State of Charge
SOEL	Solid Oxide Electrolysis
SoH	State of Health
TRL	Technology Readiness Level
TSO	Transmission System Operator
UBA	Umweltbundesamt
WACC	Weighted Average Cost of Capital
WTO	World Trade Organisation
WtW	Well-to-Wake

List of Symbols

<i>Symbol</i>	<i>Description</i>	<i>Unit</i>
H	Enthalpy	kJ mol^{-1}
w_{real}	Real specific work	kWh kg^{-1}
w_{rev}	Specific reversible work	kWh kg^{-1}
η_{Co}	Compressor efficiency	%
z_m	Mean real gas factor	—
T_{El}	Compressor inlet temperature	K
n	Polytropic coefficient	—
p_{El}	H ₂ storage pressure	bar
p_{El}	Outlet pressure electrolyzer	bar
C_t	Annual cost	EUR
A_t	Annual ammonia output	t_{NH_3}
E	Equity share	%
D	Debt share	%
r_e	Investors equity IRR	—
r_d	Loan interest rate	—
T	Corporate tax rate	—
E	Total emissions	$\text{gCO}_2\text{eq MJ}^{-1}$
E_F	Total emissions from fossil fuel comparator	$\text{gCO}_2\text{eq MJ}^{-1}$
e_i	Emissions form elastic inputs	$\text{gCO}_2\text{eq MJ}^{-1}$
e_p	Emissions form processing	$\text{gCO}_2\text{eq MJ}^{-1}$
e_{td}	Emissions from transport and distribution	$\text{gCO}_2\text{eq MJ}^{-1}$
e_u	Emissions from fuel combustion	$\text{gCO}_2\text{eq MJ}^{-1}$
e_{CCS}	Emission savings from CCS	$\text{gCO}_2\text{eq MJ}^{-1}$
M	Molar mass	g mol^{-1}
ω	Mass fraction	—
$E_{\text{RES},t}$	El. energy from RES	MWh
$P_{\text{RES},\text{nom},i}$	Rated power of RES asset i	MW
$CF_{i,t}$	Capacity factor	—
$SOC_{\text{BESS},t}$	BESS state of charge	%
$SOC_{\text{BESS},\text{min}}$	Minimum required BESS state of charge	%

List of Symbols

Symbol	Description	Unit
$E_{\text{BESS},t}$	Current total el. energy stored in BESS	MWh
$E_{\text{BESS},\text{cap},0}$	Initial maximum capacity BESS	MWh
δ_{cap}	Annual capacity degradation BESS	%
$E_{\text{BESS},\text{cap},t}$	Current maximum capacity BESS	MWh
$E_{\text{BESS},t-1}$	Previous total el. energy stored in BESS	MWh
$E_{\text{BESS},\text{out},t}$	El. energy supplied from BESS	MWh
η_{dis}	BESS discharge efficiency	MWh
$E_{\text{BESS},\text{dis},t}$	El. energy discharged from BESS	MWh
$E_{\text{BESS},\text{char},t}$	El. energy charged to BESS	MWh
η_{cha}	BESS charge efficiency	MWh
$E_{\text{BESS},\text{in},t}$	El. energy moved to BESS	MWh
$E_{\text{BESS},\text{loss},t}$	BESS losses	MWh
$P_{\text{BESS},\text{nom}}$	Rated power BESS	MW
$m_{\text{H}_2,\text{El},t}$	Electrolyzer H ₂ output	t _{H2}
$E_{\text{El},t}$	Electrolyzer el. energy input	MWh
$E_{\text{El},\text{RES},t}$	Electrolyzer el. energy input from RES	MWh
$E_{\text{El},\text{BESS},t}$	Electrolyzer el. energy input from BESS	MWh
$\text{SEC}_{\text{El},t}$	Current specific el. energy demand electrolyzer	MWh t _{H2} ⁻¹
$\text{SEC}_{\text{El},0}$	Initial specific el. energy demand electrolyzer	MWh t _{H2} ⁻¹
δ_{El}	Annual efficiency degradation electrolyzer	%
$m_{\text{H}_2,\text{El} \rightarrow \text{Syn},t}$	H ₂ mass flow from electrolyzer to Haber-Bosch	t _{H2}
$m_{\text{H}_2,\text{El} \rightarrow \text{Co},t}$	H ₂ mass flow from electrolyzer to compressor	t _{H2}
$P_{\text{El},\text{nom}}$	Rated power electrolyzer	MW
$\lambda_{\text{El},\text{min}}$	Minimum turn down rate electrolyzer	%
$E_{\text{Co},t}$	Compressor el. energy input	MWh
SEC_{Co}	Specific el. energy demand compressor	MWh t _{H2} ⁻¹
$E_{\text{Co},\text{RES},t}$	Compressor el. energy input from RES	MWh
$E_{\text{Co},\text{grid},t}$	Compressor el. energy input from grid	MWh
$E_{\text{Co},\text{BESS},t}$	Compressor el. energy input from BESS	MWh
$m_{\text{H}_2,\text{Co} \rightarrow \text{St},t}$	H ₂ mass flow from compressor to H ₂ storage tank	t _{H2}
$\text{CI}_{\text{H}_2,\text{Co} \rightarrow \text{St},t}$	Carbon intensity of H ₂ moved to H ₂ storage tank	gCO ₂ eq MJ ⁻¹
$\text{CI}_{\text{H}_2,\text{Co} \rightarrow \text{St},\text{max}}$	Maximum allowed carbon intensity of H ₂	gCO ₂ eq MJ ⁻¹
CI_{grid}	Grid carbon intensity	gCO ₂ eq MJ ⁻¹
$\mathcal{B}_t$	Set of H ₂ batches stored in H ₂ storage tank	—

List of Symbols

Symbol	Description	Unit
β_i	Individual H ₂ batch consisting of (t_i , CI_i , m_i)	—
$SOC_{St,t}$	H ₂ storage state of charge	%
$SOC_{St,min}$	Minimum required H ₂ storage state of charge	%
$m_{H_2,St,t}$	Total H ₂ stored in H ₂ storage tank	t _{H2}
$m_{H_2,St,cap}$	Maximum H ₂ storage capacity	t _{H2}
$CI_{H_2,St,t}$	Weighted average carbon intensity of stored H ₂	gCO ₂ eq MJ ⁻¹
$m_{H_2,St \rightarrow Syn,t}$	H ₂ mass flow from H ₂ storage to Haber-Bosch	t _{H2}
$CI_{H_2,St \rightarrow Syn,t}$	Carbon intensity of H ₂ moved to H ₂ Haber-Bosch	gCO ₂ eq MJ ⁻¹
$m_{NH_3,t}$	Haber-Bosch NH ₃ output	t _{NH3}
$m_{H_2,Syn,t}$	Haber-Bosch H ₂ input	t _{H2}
SHC_{Syn}	Specific H ₂ demand Haber-Bosch	t _{H2} t _{NH3} ⁻¹
$E_{Syn,t}$	Haber-Bosch el. energy input	MWh
SEC_{Syn}	Specific el. energy demand Haber-Bosch	MWh t _{NH3} ⁻¹
$E_{Syn,RES,t}$	Haber-Bosch el. energy input from RES	MWh
$E_{Syn,grid,t}$	Haber-Bosch el. energy input from grid	MWh
$E_{Syn,BESS,t}$	Haber-Bosch el. energy input from BESS	MWh
$CI_{NH_3,t}$	Carbon intensity of NH ₃ output	gCO ₂ eq MJ ⁻¹
CI_{Budget}	Available carbon intensity budget	gCO ₂ eq MJ ⁻¹
CI_{RFNBO}	RFNBO carbon intensity threshold	gCO ₂ eq MJ ⁻¹
CI_{others}	Carbon intensity of downstream processes	gCO ₂ eq MJ ⁻¹
$P_{Syn,nom}$	Rated power Haber-Bosch	MW
$\lambda_{Syn,min}$	Minimum turn down rate Haber-Bosch	%
$E_{Grid,t}$	Total el. energy supplied from grid	MWh
$E_{plant,t}^{nom}$	Total el. energy demand of plant at nominal load	MWh
$E_{plant,t}^{min}$	Total el. energy demand of plant at minimum load	MWh
γ_{max}	Maximum share of grid el. energy consumption	—
$E_{BESS,out,t}^{pot}$	Maximum available el. energy from BESS	MWh
$m_{H_2,St \rightarrow Syn,t}^{pot}$	Maximum available H ₂ from H ₂ storage	t _{H2}

1 Introduction

This chapter introduces the background, motivation, and regulatory context for RFNBO-compliant ammonia production. It outlines the thesis objective, defines the research questions, and presents the methodological approach used to develop and apply the simulation model.

1.1 Motivation and Background

In 2024, the global average temperature exceeded 1.5 °C above pre-industrial level for the first time over a full calendar year (Copernicus Climate Change Service, 2025). This development highlights the urgency of reducing greenhouse gas emissions (GHG) from fossil fuel consumption. The European Union has adopted climate policies like the EU Green Deal and the renewable energy directive (REDII) to promote the use of renewable energies. They establish legally binding targets to scale up renewable energy consumption, decarbonize key sectors and incentivise the transition away from emission intensive fossil fuels.

Some sectors, including shipping, aviation, and high-temperature industrial processes, cannot be decarbonized through renewable electricity integration alone. These so-called hard-to-abate sectors require energy-dense, transportable fuels. In this context, renewable hydrogen and its derivatives are expected to play a key role in enabling emission reductions (IRENA, 2024a). Under current EU legislation, three main production pathways for alternative fuels are defined:

- (1) Low-carbon fuels produced from fossil sources in combination with carbon capture, utilization, and storage (CCUS).
- (2) Biofuels derived from biomass.
- (3) Renewable fuels of non-biological origin (RFNBO) produced via electrolysis powered by renewable electricity.

This work focuses on RFNBOs, and specifically on renewable ammonia (NH₃). As a hydrogen-based fuel produced from electrolytic hydrogen and nitrogen, ammonia could be used as a hydrogen carrier for EU imports or as direct maritime fuel.

Project announcements for industrial scale Power-to-Ammonia (P2A) projects have been increasing (I.e. AM Green ammonia, Hynfra). Though, most projects are still in planning stages and only few final investment decisions (FID) have been announced. Barriers include high production costs, limited operating experience, and complex regulatory requirements (Narciso et al., 2025). Only fuels that meet the RFNBO criteria defined in REDII and its delegated acts ((EU) 2023/1184, (EU) 2023/1185) can be used to comply with RFNBO specific mandates and benefit from associated green premium pricing. These criteria include hourly matching between renewable electricity generation and consumption, additionality, geographic correlation, and a minimum 70 % reduction in lifecycle GHG emissions compared to a fossil benchmark.

Subsequently, these rules introduce specific constraints that directly affect system design and operation. For RFNBO ammonia projects, this adds a regulatory layer to already complex technical and economic challenges.

Current modelling tools often focus on techno-economic performance or lifecycle emissions but do not fully integrate the operational logic required for RFNBO compliance. As a result, early-stage project assessments may overlook feasibility gaps caused by regulatory constraints.

This thesis addresses that gap by developing a simulation model for P2A systems that explicitly includes REDII compliance logic. The model combines renewable input and storage variability, plant operation constraints, and regulatory requirements to assess the technical and economic performance of RFNBO ammonia production.

1.2 Objective and Research Questions

The objective of this thesis is to develop a Python-based simulation framework for P2A systems that operate under the regulatory requirements for RFNBOs. The focus lies on grid-connected systems in countries where the share of renewable electricity remains below 90 %. Therefore, hourly correlation between renewable generation and electricity use as defined in the REDII and its delegated acts will be required. The framework will simulate the time-resolved operation of all major process units and evaluate system performance under fluctuating renewable supply. REDII compliance will be embedded through hourly electricity matching and traceable GHG emissions accounting. The model will be applied over multi-year periods to assess the operational feasibility and commercial viability of RFNBO ammonia production. The simulation results will be used to derive key technical and commercial performance indicators (KPI). A sensitivity analysis will be conducted to examine how changes in renewable availability and storage configuration affect overall system performance.

This leads to the following research questions:

- (1) How can a simulation framework for RFNBO-compliant P2A systems be designed to consistently capture the technical, economic, and regulatory interdependencies under sub-90 % renewable grid conditions, particularly accounting for hourly correlation requirements?
- (2) How does renewable energy availability affect the operation of a P2A process and its commercial performance across the project lifetime?
- (3) How does storage integration affect the operation of a P2A process and its commercial performance across the project lifetime?

1.3 Methodology

The methodology applied in this thesis follows a structured, model-based approach to assess the technical and economic performance of RFNBO-compliant P2A systems. The development of the simulation model is grounded in regulatory, technical, and economic requirements and is implemented in Python using rule-based dispatch logic.

First, the relevant regulatory conditions for RFNBO certification are reviewed. The focus is on the criteria defined in the REDII delegated acts, particularly hourly correlation, additionality, and greenhouse gas emission thresholds. These requirements are translated into quantifiable constraints that can be integrated into the simulation logic.

Next, the technical characteristics and interdependencies of the P2A system components are defined. Key assumptions regarding performance parameters and cost data are derived from literature. Technical constraints such as minimum load levels, part-load behavior, and degradation effects are included in the model structure where relevant.

The simulation framework is developed to operate on an hourly time scale over multi-year project durations. System operation is governed by rule-based logic to reflect realistic dispatch behavior while maintaining mass and energy balance across all units. REDII compliance checks are implemented to validate hourly matching and emissions thresholds throughout the simulation period.

The model is first validated through plausibility checks under controlled test scenarios to ensure correct implementation of process logic and regulatory constraints. Following validation, the framework is applied to conduct a sensitivity analysis. This analysis investigates the influence of renewable energy availability and storage configuration on the technical feasibility and commercial viability of the system.

This methodology allows for a consistent, regulation-aware assessment of early-stage P2A system configurations under realistic boundary conditions.

2 Theoretical Background

In this chapter, the needed theoretical background for the thesis is explained. This chapter covers the key regulatory, technical, and economic concepts relevant to RFNBO-compliant ammonia production. It explains the EU policy framework, core components of the P2A process, and the modelling approach used in this thesis. These foundations are essential for understanding the simulation framework and its compliance with REDII requirements.

2.1 EU Policy Landscape

2.1.1 EU Green Deal and Fit for 55 Package

In 2019 the European commission presents the EU Green Deal. The EU Green Deal serves as the overarching policy initiative aiming to make Europe the first climate-neutral continent by 2050. It establishes a holistic approach to sustainability, integrating climate policy with energy, transport, agriculture and industry. To achieve this, it sets forth legally binding climate targets, such as the commitment to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels (European Commission, 2019).

The Fit for 55 package is a collection of legislative proposals that operationalize the objectives of the EU Green Deal by adjusting existing policies and introducing new regulatory mechanisms (European Commission, n.d.).

2.1.2 EU ETS and CBAM

The EU Emissions Trading System (EU ETS) is a market mechanism to reduce greenhouse gas emissions in power generation and energy intensive industries. By imposing a cap on total emissions and allowing trading of emission allowances, the system establishes a dynamic carbon price signal that incentivizes emission reductions. Emissions reduction are achieved by means of efficiency optimization or adaptation of low-carbon and renewable alternatives, like renewable hydrogen and its derivatives (“Delivering a Climate Neutral Europe,” 2024, chap. 3). To preserve the competitiveness of European industry under rising carbon costs and prevent production from shifting to regions with laxer climate regulations (carbon leakage) the EU introduced the Carbon Border Adjustment Mechanism (CBAM). CBAM imposes a carbon cost on selected imported goods, such as steel, fertilizers, and ammonia, thereby aligning the carbon cost of imports with that of domestic production (Graichen et al., 2023). Together, the EU ETS and CBAM aim to reflect the true environmental cost of industrial GHG emissions in market prices. This creates a level playing field for low-emission technologies such as RFNBO ammonia and supports the broader transition toward climate-neutral production systems. A detailed explanation of both mechanisms is provided in Appendix A.1 and A.2.

2.1.3 Renewable Energy Directive

The Renewable Energy Directive (RED) is the EU's primary legislative framework for promoting the use of renewable energy across all sectors, ensuring a stable and predictable policy environment for member states (Clean Hydrogen JU, 2025).

Originally introduced as Directive 2009/28/EC, it set a binding target of 20% renewable energy in the EU's gross final energy consumption by 2020. According to Eurostat's renewable energy statistics, the EU exceeded this target, achieving a 22% renewable energy share in 2020 (Eurostat, 2022).

Building on this progress, the Renewable Energy Directive (2018/2001/EU), commonly referred to as REDII, introduced a binding target of 32% renewable energy by 2030, with a possible upward revision (European Union, 2018). However, with the introduction of the European Green Deal and more ambitious climate targets, further amendments were proposed. On 14 July 2021, the European Commission suggested increasing the 2030 target to 40%, later raising it to 45% under the REPowerEU plan to accelerate the transition away from Russian fossil fuels. This plan focused on energy savings, clean energy production, and supply diversification (European Commission, n.d.).

The latest revision, Renewable Energy Directive (EU/2023/2413) – or REDIII, formally sets the EU's binding renewable energy target at a minimum of 42.5% by 2030, with an aspirational goal of 45%, nearly doubling the current renewable energy share. The directive entered into force on 20 November 2023, applying to all EU member states (European Union, 2023a). A detailed overview of RED targets, an explanation of multipliers and the transposition of the REDII into national law at the example of Germany (37th BImSchV) are provided in Appendix A.3, A.4 and A.5.

Among the measures to reach the binding target for renewable energy consumption, the REDII introduces and defines renewable fuels of non-biologic origin (RFNBO).

- Article 27 establishes the conditions under which electricity used for RFNBO production qualifies as renewable, ensuring that hydrogen and its derivatives contribute to additional renewable energy deployment.
- Article 28 specifies how GHG emissions savings must be calculated for RFNBOs, ensuring compliance with the minimum 70% reduction threshold compared to fossil fuel comparators.

2.1.4 REDII Delegated Acts

In February 2023, the commission enacted two delegated acts required under RED II articles 27 and 28, outlining requirements for RFNBOs. These delegated acts enable RFNBOs contribution to REDII binding targets, by establishing certifiable standards of Power-to-X (PtX) pathways for “green” hydrogen and its derivatives, such as ammonia, methanol, and synthetic hydrocarbons (European Commission, 2023).

The first delegated act, Delegated Regulation (EU) 2023/1184, defines the requirements for when electricity used in the production of RFNBO can be counted as fully renewable. The

concepts of additionality, temporal correlation and geographical correlation are introduced and explained (European Union, 2023b).

The second delegated act, Delegated Regulation (EU) 2023/1185, defines the methodology for calculating RFNBO greenhouse gas (GHG) emissions savings. RFNBOs must achieve at least a 70% reduction in GHG emissions compared to fossil fuels, assessed using a well-to-wake (WtW) approach covering all lifecycle emissions from electricity generation to final fuel use. The methodology considers emissions from upstream stages, electricity grid use, processing and transportation, specifying criteria for using eligible sustainable sources in RFNBO production (European Union, 2023c).

The regulations subsequent increase in operational complexity when balancing RFNBO production from variable renewable supply, is a focus of this thesis as outlined by the research questions in chapter 1.2. A detailed requirement analysis of RFNBO compliant ammonia production derived from the delegated acts will be outlined in chapter 3.

2.2 Elements of the P2A Process

The Power-to-Ammonia (P2A) process is a specialized variant of the broader Power-to-X (PtX) concept, in which renewable electricity is converted into chemically stored energy through the synthesis of ammonia using water, air, and renewable electricity. According to (Narciso et al., 2025) a P2A process via water electrolysis necessitates four core components: (i) a renewable energy (RE) generation system, (ii) an electrolyzer for hydrogen (H_2) production, (iii) an air separation unit (ASU) to extract nitrogen (N_2), and (iv) a Haber-Bosch (HB) synthesis loop where H_2 and N_2 react to form ammonia. These units constitute the essential framework of any P2A system, with renewable electricity powering the subsequent chemical pathways that facilitate ammonia production.

While the four core components define the minimum functional structure of a P2A system, additional auxiliary units can be integrated to improve operational flexibility and reliability. These optional components form a superstructure that enables various P2A configurations tailored to different technical and economic conditions. Such auxiliary systems are critical, as the core P2A process units are not inherently designed to track instantaneous fluctuations in renewable energy supply.

Key auxiliary units typically include:

- Power curtailment mechanisms, which are necessary to manage surplus renewable power when generation exceeds P2A demand.
- Grid connection, allowing electricity to be bought or sold based on market conditions and economic constraints (e.g., purchasing during low-price periods).
- Battery energy storage systems (BESS), which store excess renewable electricity and discharge it during periods of low availability.
- Hydrogen and nitrogen storage, facilitating the buffering of intermittent renewable energy by storing reactants for continuous ammonia synthesis.

For the purposes of this work, all auxiliary units are included in the P2A system model. The following sections provide a brief introduction of each core and auxiliary unit, along with an

overview of the conventional Haber-Bosch process utilizing steam methane reforming (SMR) as a baseline reference for comparison.

2.2.1 Renewable Electricity Source

There are several different renewable electricity sources (RES). In this context, 'renewable' refers to technologies that have minimal net GHG emissions. These sources include wind, solar, hydro, and biomass energy. Wind power and photovoltaic (PV) solar energy are the most utilized due to their scalability, declining costs, and global availability, as is shown by the gradually increasing share of total energy consumption from wind and PV worldwide (Ritchie and Rosado, 2020). For this work, only RE generation from wind and PV will be considered.

Wind Power

Wind is a result of uneven heating of the Earth's surface by the sun, leading to pressure differences that drive air movement. During wind power generation, the kinetic energy of those moving air masses is partially converted into mechanical energy, which is then transformed into electricity through wind turbines. A typical wind turbine consists of three main components: the rotor blades mounted on the turbine's hub; the nacelle, which houses the generator and gearbox; and the tower, which elevates the turbine to higher altitudes where wind speeds are more stable and stronger. Wind passing over the turbine's rotor blades (kinetic energy) generates torque on the rotor hub, causing rotational motion (mechanical energy) that is transferred via the shaft to the generator rotor, where it induces an electric current in the stator windings (electrical energy). The efficiency of wind energy conversion depends primarily on wind speed and the area covered by the rotor, with the power output of a wind turbine being directly proportional to the cube of wind velocity. This means that even small increases in wind speed can result in significantly higher electricity generation. Wind turbines are categorized into onshore and offshore systems, with modern onshore turbines typically ranging from 3 to 4 MW and offshore models reaching capacities of 8 to 12 MW due to the more consistent wind conditions over open water (IRENA, 2024b). Modern industrial scale wind turbines are of the "Danish design" with a three-blade rotor on a horizontal axis of rotation and active wind alignment (yaw system).

Full load hours (FLH) represent the equivalent hours a renewable system (wind or PV) operates at full capacity to match its annual energy output. The capacity factor is the ratio of actual energy produced to the theoretical maximum, indicating efficiency and resource availability. This definition can be translated to any producing unit (i.e. Haber-Bosch synthesis, electrolysis, etc), giving a measure of its utilization over a defined period, usually one year. Onshore wind turbines in Germany achieve capacity factors between 20% and 35% annually, depending on location, translating to approximately 1,800 to 3,200 full load hours (Kost et al., 2024).

Photovoltaic Power

Photovoltaics mainly utilizes monocrystalline and polycrystalline solar cells. Solar cells consist of a semiconductor material that sets electrons in motion under the influence of sunlight and thus generates electricity. This direct current is converted into alternating current via an inverter

and fed into the grid. PV system design is mainly dependent on relative latitude to the equator as horizontal irradiance decreases further north or south. This must be compensated by increasing tilt angles, thereby promoting shading effects and increasing areal demand for equivalent systems. For Germany, the specific areal demand for PV is at around one hectare per MW. PV generation is dependent on irradiation intensity, leading to a bell curve shaped typical daily load profile in the hours from sunrise to sunset. Seasonal changes through celestial movement cause the curve to compress and stretch in vertical and horizontal direction between summer and winter. Typical FLH for PV in Germany range from 900 in the north up to 1300 in the south (Kost et al., 2024).

2.2.2 Grid Connection

In grid-connected P2A system designs, the contracted RE is transported from the RES via the public grid to the ammonia synthesis plant. In addition to general transmission losses, this means in practice, that the supply of RES is susceptible to grid congestion and subsequent redispatch measures by the Transmission System Operator (TSO). This may affect the contracted RES, resulting in unplanned RES shortages that have a negative impact on the continuous operation of critical processes such as the Haber-Bosch process (see chapter 2.2.6). At the same time, a grid connection provides access to the electricity market. Electricity shortfalls from contracted RES can be made up by purchasing electricity from the spot market. Otherwise-curtailed surplus electricity can be sold off, potentially reducing losses from contracted and paid for unused electricity (Narciso et al., 2025). In this work, the focus is on RFNBO compliance rather than on economic optimisation in the electricity market, resulting in a simplified modelling of market interactions and a focus on the regulatory implications of grid use in the P2A process (see chapter 3).

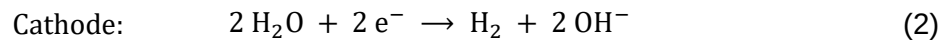
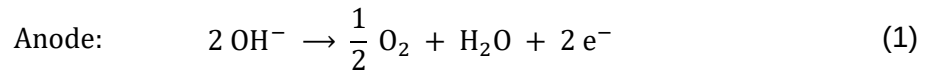
2.2.3 BESS

Battery energy storage systems in a P2A process serve the purpose of smoothing out potentially rampant power drops and surges from supplying RES and in general enable a continuous operation of critical P2A processing units. Batteries typically consist of two electrodes immersed in an electrolyte, where energy is stored and released through electrochemical reactions. During charging, an external voltage drives electrons from the positive electrode (cathode) to the negative electrode (anode), converting electrical energy into chemical energy. In the discharge process, this reaction is reversed, allowing stored energy to be released as electricity. However, each charge-discharge cycle incurs energy losses, which vary depending on the battery's efficiency. Over time, repeated cycling leads to battery degradation, reducing its capacity, efficiency and overall lifespan, which varies depending on the battery chemistry and operating conditions. Various battery technologies are employed across different applications, with the most widely used being lithium-ion, lead-acid and alkaline batteries (Kurzweil and Dietlmeier, 2018; Sterner and Stadler, 2014; Vykhodtsev et al., 2022). This work specifically focuses on lithium-ion battery technology.

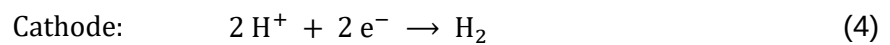
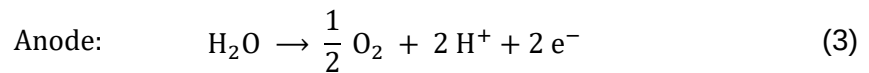
2.2.4 Water Electrolysis

For P2A processes the hydrogen production is typically done by means of water electrolysis, whereby electricity is used to split water into hydrogen and oxygen. This electrochemical reaction occurs in an electrolyzer (EL), which consists of two electrodes immersed in liquid- or enclosing a fixed-electrolyte. The technically relevant variations of this technology today are alkaline electrolysis with a liquid basic electrolyte (AEL), acid electrolysis with a polymer solid electrolyte (PEMEL) and high-temperature electrolysis with a solid oxide ceramic as electrolyte (SOEL) (Metz et al., 2022). SOEL will not be considered in this work, as their Technology Readiness Level (TRL) is not mature enough for a large-scale installation (Kurzweil, 2018; Sebbahi et al., 2024).

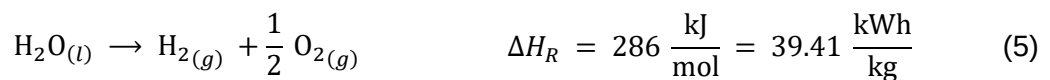
AEL operates with a liquid potassium hydroxide (KOH) electrolyte (25–30%) and nickel-based electrodes. During electrolysis, H_2 is generated at the cathode, while OH^- anions migrate through a gas-tight diaphragm to the anode, where they release electrons to form O_2 and water (Equations (1) and (2)). The system functions at 50–80°C and 20–50 bar and has a larger spatial footprint due to its circulating electrolyte (Kurzweil, 2018).



PEMEL in contrast, uses a solid polymer membrane that allows proton migration between electrodes. O_2 is produced at the anode, while H_2 forms at the cathode as protons permeate through the membrane (Equations (3) and (4)). Unlike AEL, PEMEL requires precious metal electrodes (iridium and platinum), making it more cost-intensive despite its compact design and faster response time (Kurzweil, 2018).



The summative reaction of anode and cathode is shown in equation (5). The specific reaction enthalpy (ΔH_R) of hydrogen is approximately 33.35 kWh/kg when based on gaseous water, or 39.41 kWh/kg when based on liquid water, under standard conditions (298.15 K and 1,013 mbar) (Kurzweil, 2018). These values correspond to the lower heating value (LHV) and higher heating value (HHV) of hydrogen respectively. According to Equation (5), producing 1 kg of hydrogen requires 8.94 kg of water, based on stoichiometric calculations. This process also yields 7.94 kg of oxygen per kilogram of hydrogen produced (Kurzweil, 2018; Metz et al., 2022).



The reaction in Equation (5) takes place considering various losses, which is why more energy is required than is stored chemically in hydrogen. Losses include incomplete reactions at the

electrodes, auxiliary consumers (pumps, compressor) and chemical overpotentials. The overall system efficiency of water electrolysis is dependent on the operational load of the electrolyzer as is depicted in Figure 1. Electrolyzer manufacturers often include a stack efficiency measure that excludes auxiliary consumer losses (Cummins, n.d.). Operation of EL above nominal load, although technically possible (Rezaei et al., 2024), will not be considered in this thesis.

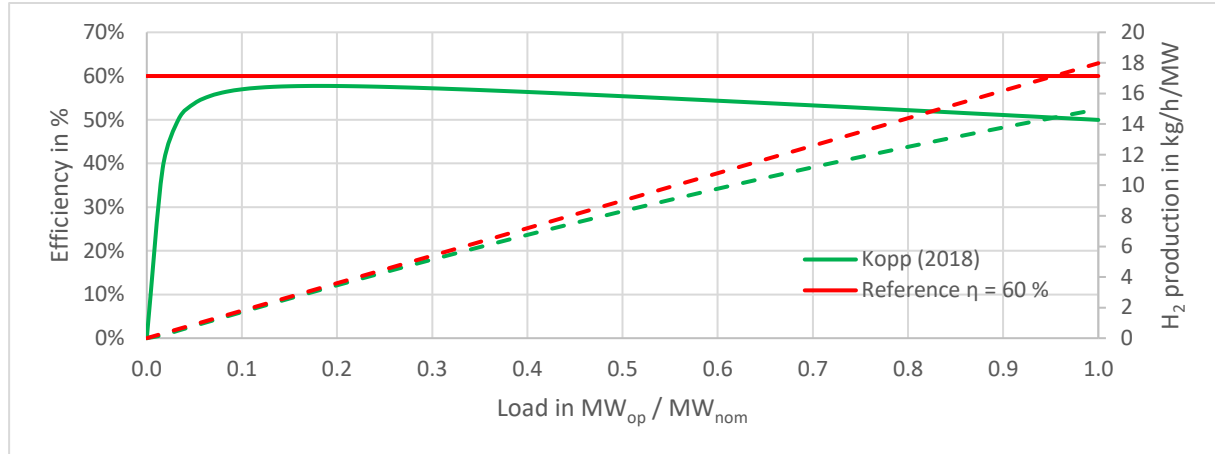


Figure 1: Primary y-axis: Comparison of the load dependent system efficiency of a PEMEL published by Kopp (2018) with a constant reference efficiency at $\eta = 60\%$ (solid lines). Secondary y-Axis: specific H_2 production rates (dashed lines). Efficiencies are referred to the LHV.

Figure 1 shows that the efficiency at small operating loads drops significantly. This can be explained by an increase in the relative consumption of the auxiliary consumers that feature constant, rather than linear, demand for lower operating loads (Kopp, 2018). Therefore, a minimum operating load must be considered. For simplification, a constant reference efficiency will be assumed in this thesis. As discussed by Virah-Sawmy et al. (2024) this can lead to over- or under estimation of H_2 production from electrolysis, depending on the reference efficiency and minimum load considered.

2.2.5 Hydrogen Compression and Storage

Under standard conditions, hydrogen exhibits a high gravimetric energy density, amounting to 39.4 kWh/kg (HHV), but a very low volumetric energy density of only 3.54 kWh/Nm³ (HHV). In contrast, gasoline fuel has a lower energy content per mass unit (11.9 kWh/kg), but a significantly higher energy density per volume (8540 kWh/Nm³). As a result, hydrogen storage systems must address the challenge of its low volumetric energy density in order to enable compact and efficient storage (Kurzweil and Dietlmeier, 2018).

There are several methods for storing hydrogen, with the most technically mature being compressed gas storage and liquid hydrogen storage. In compressed gas systems, hydrogen is stored at high pressures, while liquid hydrogen systems rely on cooling the gas to -253 °C to achieve liquefaction. Additional approaches include material-based storage, where hydrogen is adsorbed or absorbed into solid materials (Usman, 2022).

This work focuses on compressed hydrogen storage in pressure vessels, which are typically made of steel or composite materials. These vessels can store hydrogen at pressures of up to 1,000 bar, although for industrial applications, lower-cost steel tanks operating at 200–300 bar are commonly used (Usman, 2022).

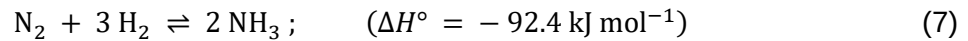
Assuming polytropic compression conditions, the calculation of the specific compressor work (kJ/kg_{H₂}) is shown in Equation (6). The theoretical specific work required for compression (w_{rev}) depends on the pressure difference between the gas pressure at EL outlet (p_{El}) and current (p_{St}) storage pressure, the gas temperature at the compressor inlet (T_{El}). The actual specific work required (w_{real}) then further depends on the compressor efficiency (η_{Co}). As the storage tank adheres to the real gas law, the higher the state of charge (SOC), the higher the pressure difference between EL outlet and storage, and the more work is required to store additional H₂ (Willner, 2021).

$$w_{real} = w_{rev} \cdot \frac{1}{\eta_{Co}} = \frac{z_m \cdot R \cdot T_{El}}{M_{H_2}} \cdot \frac{n}{n-1} \cdot \left[\left(\frac{p_{St}}{p_{El}} \right)^{\frac{n-1}{n}} - 1 \right] \cdot \frac{1}{\eta_{Co}} \quad (6)$$

2.2.6 Haber-Bosch Process

The conventional Haber-Bosch process is the dominant route for industrial ammonia production, primarily relying on fossil feedstocks with around 50% from natural gas, 31% from oil, and 19% from coal (Narciso et al., 2025). Among these, steam methane reforming is regarded as the best available technology (BAT) due to its high efficiency and comparatively low CO₂ emissions (Smith et al., 2020). Emission intensities vary widely by feedstock, from 1.9 tCO₂/tNH₃ for SMR to 16.7 tCO₂/tNH₃ for coal-based processes (Erfani et al., 2024). Although renewable ammonias commercial initiation dates back to 1921, its global share remains marginal with only 0.02 MMT out of 182 MMT total ammonia production in 2021 (Bora et al., 2024).

The highly exothermic ammonia synthesis reaction takes place in a fixed-bed catalytic reactor (converter), that is at the core of the ammonia synthesis (see Figure 2). Equation (7) shows the reversible reaction (Schlögl, 2008):



The chemical equilibrium of the reversible reactions is favourable towards ammonia conversion at high pressures (Le Chatelier's principle) and low temperatures (exothermal reaction; $\Delta H^\circ < 0$). At the same time low temperatures dampen reaction kinetics, decreasing overall reactivity (Schlögl, 2008). Optimal performance is achieved at around 150–350 bar and 400–450°C, striking a favourable balance between thermodynamic equilibrium and sufficient reaction kinetics. Since single-pass conversion rates remain low (15–25%), unreacted gases are continuously recycled. Ammonia is separated from the cycle stream via condensation at -5 to -25°C. Inert gases, predominantly argon, are purged to avoid their accumulation, which would otherwise reduce reactor efficiency. Prior to recycling, the syngas stream is replenished to restore the target H₂-to-N₂ ratio (typically 1-to-2.5 – 1-to-3.0) and recompressed. Heat exchangers are employed to recover thermal energy from the reactor effluent and to preheat the

incoming feed stream, thereby improving energy efficiency (Bora et al., 2024; Narciso et al., 2025; Smith et al., 2020).

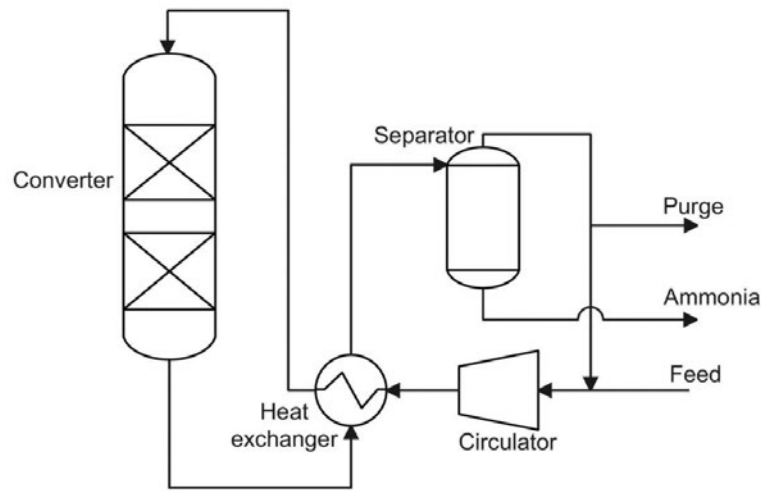


Figure 2: Ammonia synthesis loop in a simple form (Erfani et al., 2024)

In conventional HB systems based on SMR, nitrogen is introduced through the secondary reformer where oxygen is consumed. Nitrogen and argon remain as inert gases, thus eliminating the need for a dedicated nitrogen production step (Narciso et al., 2025). In contrast, P2A systems utilizing high-purity hydrogen from water electrolysis require nitrogen to be supplied from an air separation unit. The predominant ASU technology is cryogenic separation, as employed in processes licensed by companies such as Linde. Here, air is compressed, purified and cooled to cryogenic temperatures. Through fractional distillation, nitrogen – having the lowest boiling point – is separated at the top of the column, while oxygen and argon are removed further down, resulting in a high-purity nitrogen stream suitable for ammonia synthesis (Grenier and Petit, 1986). Alternative technologies include pressure swing adsorption.

Over decades, the HB process has been optimized for high energy efficiency through extensive heat integration and turbine-driven compression systems. In conventional setups, large compressors – including those for SMR process air, makeup syngas, refrigeration, and recycle loops – are powered by steam turbines that utilize waste heat from the SMR reactors (Smith et al., 2020). This recovered heat is no longer available in P2A systems that do not include SMR. Consequently, the energy demand of the HB process – mainly that of the ASU and synthesis loop – must be covered by RE from RES, BESS, or by grid imports (Klyapovskiy et al., 2021).

A significant challenge in integrating the HB process into flexible renewable-based systems lies in its limited dynamic operability. Traditional HB plants are designed for continuous operation with stable feedstock supply and consistent pressure-temperature conditions. Frequent load changes induce thermal and mechanical stress, leading to material fatigue and catalyst degradation (Wang et al., 2023). As a result, the HB process exhibits far less operational flexibility than electrolysis. Parameters such as ramp rates, partial load ranges, cold start requirements and minimum downtime following shutdowns critically define its adaptability (Klyapovskiy et al., 2021). These constraints will be further analysed in Chapter 4.

2.3 Modelling and Simulation

Modelling and simulation are key tools for analysing complex energy systems. While a model abstracts the structure and behaviour of a system, a simulation is used to explore system dynamics under defined boundary conditions. In PtX applications, such simulations support the assessment of technical feasibility, the system performance under variable renewable supply, and early-stage project evaluation. Methodologically, a distinction is made between deterministic models, which yield consistent results for given inputs and stochastic models, which incorporate randomness to reflect uncertainties such as market fluctuations or variable demand (Downey, 2023).

Another distinction lies between optimization-based and rule-based simulation approaches. Optimization models, such as those based on mixed-integer linear programming (MILP), are widely applied in energy systems research to identify cost-optimal system configurations or dispatch strategies. MILP allows for the simultaneous consideration of continuous and discrete decision variables and is particularly suited for investment and operational optimization problems. Numerous studies on PtX systems, including P2A, have adopted MILP frameworks to determine optimal sizing of process units and dispatch schedules that minimize cost or emissions while satisfying a set of technical and commercial constraints (Ince et al., 2021; Narciso et al., 2025).

However, optimization models often require simplifying assumptions to ensure linearity or tractability, which can limit their ability to represent complex, time-dependent operational behaviour and detailed regulatory constraints. Specifically, optimization approaches may not capture the full temporal granularity required for compliance with RFNBO rules under the REDII, such as the hourly correlation of renewable electricity use or the traceability of greenhouse gas emissions.

In this thesis, a deterministic, rule-based dispatch simulation is implemented to evaluate the technical feasibility and REDII compliance of a P2A plant under site-specific renewable electricity supply conditions. This approach simulates plant operation on an hourly basis, using a structured set of logical conditions to determine the operational state of each process unit (i.e. electrolyzer, storage, Haber-Bosch synthesis). The dispatch logic is designed to reflect realistic operational constraints, such as minimum load requirements and storage limitations, while ensuring temporal alignment with renewable energy input and adherence to regulatory emission thresholds. Li et al. (2024) for example uses this approach to implement a dispatch strategy for a wind-photovoltaic-electrolysis-battery system, while Modu et al. (2024) implements a rule-based EMS, arguing with simplicity, user-friendliness, practical applicability and low computational requirements of the approach.

Although rule-based simulations do not yield optimized outcomes, they offer key advantages in terms of transparency, interpretability and regulatory traceability. The approach enables a detailed analysis of system behaviour under defined configurations, making it particularly well-suited for early-stage feasibility studies, where regulatory compliance and technical operability are prioritized over economic optimality. Moreover, rule-based models are widely used in renewable energy system simulations where fluctuating supply, system flexibility and real-time constraints make optimization difficult to apply directly. The model structure is adaptable for

scenario analysis and may serve as a foundation for future integration with optimization-based frameworks.

A detailed description of the model architecture, mathematical formulation, input assumptions, and implementation is provided in Chapter 5.

2.4 Economic Assessment

The techno-economic feasibility of RFNBO ammonia production depends not only on the technical functionality and regulatory compliance of the system, but also on its economic competitiveness. In this context, economic assessments are used to evaluate the cost-effectiveness of different plant configurations and to identify parameters that influence commercial viability. The economic evaluation in this thesis is based on the levelized cost of ammonia (LCOA) as a standardized performance indicator. This approach has been applied in numerous comparable studies, that are referenced throughout this thesis (Campion et al., 2023; Ikäheimo et al., 2018; Yu et al., 2024). This chapter introduces the theoretical basis for the applied methodology and explains how the key economic indicators used in this thesis are derived.

The LCOA is defined as the total discounted cost of producing ammonia over the lifetime of the plant (net present value - NPV_{Costs}), divided by the total discounted amount of ammonia produced (net present ammonia - NPA). It accounts for capital costs, replacement costs, operating expenditures and energy procurement costs. Revenues from surplus renewable electricity sales are included as cost-reducing terms (negative cost). LCOA is calculated as:

$$LCOA = \frac{NPV_{Costs}}{NPA} = \frac{\sum_{t=0}^n \frac{C_t}{(1+r)^t}}{\sum_{t=0}^n \frac{A_t}{(1+r)^t}} \quad (8)$$

with:

- C_t : total cost per year t ,
- A_t : ammonia output per year t ,
- r : discount rate,
- n : total project lifetime

All costs and outputs are evaluated in nominal terms, meaning they include the effects of inflation. This approach aligns with typical project finance practices and reflects actual cash flows without conversion to real (inflation-adjusted) values (Aldersey-Williams and Rubert, 2019).

The LCOA represents the specific product price (in EUR/t_{NH₃}) at which the cumulative net present value (NPV) of the project equals zero, assuming all produced ammonia is sold at this constant price. In other words, the LCOA corresponds to the break-even selling price that results in an internal rate of return (IRR) equal to the applied discount rate.

The discount rate applied in the LCOA calculation is the weighted average cost of capital (WACC). It reflects the average cost of capital from both equity and debt sources, weighted by their respective shares in the financing structure of the P2A project. The WACC is considered

a key determinant of the project's financing cost and is commonly used to assess economic viability in capital-intensive infrastructure projects (Schawel and Billing, 2014). WACC is calculated as:

$$\text{WACC} = \frac{E}{E + D} \cdot r_e + \frac{D}{E + D} \cdot r_d \cdot (1 - T) \quad (9)$$

with:

- E : equity share,
- D : debt share,
- r_e : cost of equity (investors equity IRR expectation),
- r_d : cost of debt (loan interest rates),
- T : applicable corporate tax rate.

A lower WACC indicates more favourable financing conditions and leads to a lower LCOA. Higher values reflect greater investment risk or financing constraints and result in less competitive production costs. In the model, the parameters used to calculate the WACC will be treated as input variables. They may be varied to evaluate their impact on the commercial viability of the RFNBO ammonia production system.

This structured economic layer, based on LCOA and WACC, enables a meaningful evaluation of techno-economically feasible and RED II-compliant ammonia production configurations. It also supports the comprehensive aim of the thesis: to quantify how technical and regulatory constraints influence the commercial performance of P2A projects.

3 Regulatory Model-Requirement Analysis

In Chapter 3, the regulatory requirements relevant to the simulation of RFNBO-compliant ammonia production are derived from applicable EU legislation. The focus is on formalizing constraints established under Delegated Regulations (EU) 2023/1184 and 2023/1185 (henceforth referred to as DA 1184 and DA 1185, respectively), that directly impact the operation and compliance of grid-connected P2A systems. These include electricity sourcing via direct connection or PPAs from renewable installations, hourly temporal and bidding zone-based geographical correlation of renewable electricity, compliance with additionality requirements and life-cycle GHG emission savings thresholds of at least 70%. These constraints constitute the regulatory foundation for the subsequent techno-economic analysis and model implementation.

3.1 Overview of Electricity Sourcing Pathways

In the revised RED II, RFNBOs are defined as: “renewable fuels of nonbiological origin” meaning liquid and gaseous fuels whose energy content is derived from renewable sources other than biomass (EU 2023/2413 Art 1. (1g)). This concludes the general rule, that electricity sourced from installations generating renewable electricity can only be counted as fully renewable under specific conditions. To be compliant, electricity may only be generated from wind, solar (solar thermal and solar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, and hydropower. The distinction of fully renewable electricity is particularly important. If a process increases the heating value of its inputs, meaning energy is being stored, its output(s) can only be considered RFNBO, if the energy used is fully renewable. In the modelled P2A process, this only affects the electrolysis step where water (0 MJ/kg) is turned into hydrogen (120 MJ/kg) using electrical energy. In the GHG emission calculation, electricity that is considered fully renewable is accounted for with zero gCO₂eq/MJ (DA 1185 Annex A. 5).

A further key concept used in the DAs is that of bidding zones, taken from (EU) 2019/943 article 2. point (65), where it is defined as “the largest geographical area within which market participants are able to exchange energy without capacity allocation”. For most European countries, bidding zones align with national borders, though exemptions like the multinational bidding zone of DE-LU-AT (now only DE-LU) or intra-national bidding zone like Swinden’s SE 1-4 exist. The bidding zone within which the fuel production occurs is relevant, as grid carbon intensities and shares of renewable energy may be calculated based on country or bidding zone level, provided that required data of the same level of quality as published by the IEA is publicly available. As bidding zones are a concept suited to the European electricity market design, the regulations provide leeway that allows economic operators to assume equivalent concepts where bidding zones do not exist or are not clearly defined (DA 1184, Recital 3).

To claim RFNBO compliance for fuels produced via PtX pathways and to enable fuel producers to issue valid proof of sustainability (PoS) certificates, the entire supply chain must undergo regular audits. These audits must be carried out by recognized certification bodies operating under one of the EU-approved voluntary or national certification schemes for RFNBOs. As of today, three voluntary schemes have been approved by the European Commission for RFNBO certification: REDcert, ISCC and CertifHy (European Commission, n.d.). In Germany, the Federal Environment Agency (Umweltbundesamt, UBA) has formally pre-recognized four certification bodies authorized to certify RFNBO producers. Among these are TÜV Süd and DEKRA (Umweltbundesamt, 2025).

There are three paths recognized in the REDII regarding the sourcing of electricity to produce RFNBOs. These paths can be combined, resulting in four cases that will be described in the following chapters:

- Case 1: average grid mix electricity (RED Art. 27.3)
- Case 2: fully renewable electricity from directly connected renewable energy generation source (DA 1184 Art. 3)
- Case 3: fully renewable electricity supplied via the electricity grid (DA 1184 Art. 4)
- Case 4: a combination of case 1, 2 & 3

3.1.1 Average Grid Mix Electricity

As a default according to Art 27.3 in REDII, when producing RFNBO from grid electricity without fulfilment of further requirements, the share of renewable energy in the grid, as recorded two years prior to the year of production, determines the share of renewable energy stored in the product. However, as is shown in Figure 3, currently, this approach will rarely ever yield compliant RFNBO due to high grid emission intensities of EU grids and the resulting failing of the 70 % GHG saving requirement (red line).

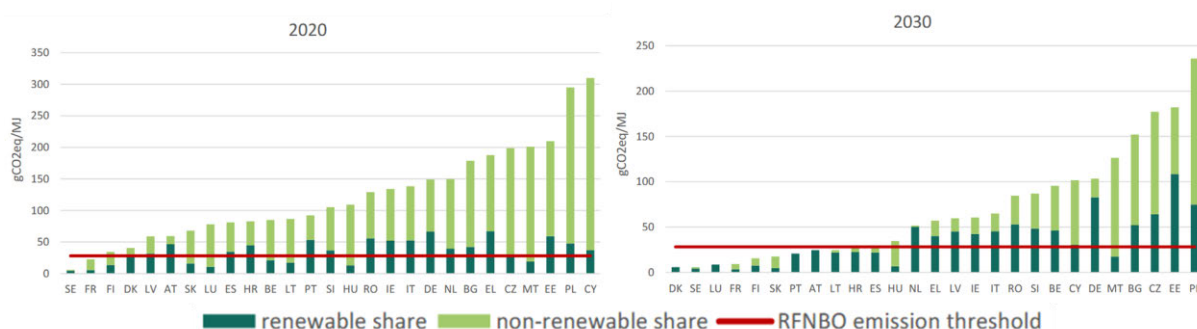


Figure 3: GHG emission intensity of hydrogen produced using grid electricity mix for European countries based on RES shares and grid carbon intensity for 2020 (left) as well as expected development until 2030 (right) (Hydrogen Europe aisbl, 2023)

With the continuous shift towards RES in European electricity generation, this will gradually open new regions where RFNBO production could be feasible from grid mix electricity alone (Hydrogen Europe aisbl, 2023). In grids that can achieve 70 % GHG saving, due to high nuclear energy shares, such as in France and Finland, the share of RFNBO in the overall production will still be small, due to low RES grid shares (IEA, 2024a, 2024b).

The goal of this thesis is to set up and discuss a rule-based simulation framework for RFNBO compliant ammonia production. Therefore, the sourcing of electricity based on the average grid mix for processes enhancing the heating value (electrolysis), without further requirement fulfilment is inadequate and must not be considered, as it could yield shares of produced ammonia that are not RFNBO compliant. However, grid electricity consumption will still be considered in the P2A process, specifically in processing steps that do not enhance the heating value of the final or intermediate products, as is outlined in chapter 3.3.

3.1.2 Fully Renewable Electricity from a Direct Connection to a RES

According to DA 1184 Art. 3, electricity sourced from an installation producing renewable energy, that shares a direct connection with the plant producing the RFNBO, can be counted as fully renewable, if it has come into operation within 36 months before the plant producing RFNBO. This is generally equivalent to the requirement of additionality outlined in chapter 3.2.1, except for the restrictions on received state aid for the renewable energy installation and the transitional phase for RFNBO installations that come into operation until the 31.12.2027. If the renewable energy installation shares a connection to the public grid, a smart metering system must be added to ensure that no electricity flow from the grid is included in the production of RFNBO. RES supply through a direct connection ‘naturally’ aligns with the requirement of temporal correlation, since electricity must either be consumed the moment it is generated, be stored, or otherwise sold off or curtailed.

In the context of this thesis, sourcing of electricity through a direct connection will therefore effectively be considered when sourcing electricity from the public grid via a renewable PPA as described in the chapter 3.2. It will however be assumed, that directly connected assets will also be connected to the grid, thus enabling potential sales of surplus electricity.

3.1.3 Fully Renewable Electricity taken from the Grid

As opposed to case 1 and 2, electricity taken from the grid can be considered 100% fully renewable, when complying with rules set out under DA 1184 art. 4. in combination with art. 5., 6. & 7. This is possible through signing one or more renewable power purchase agreements (PPA) with operators of installations generating renewable electricity and complying with the preconditions of additionality (art. 5), temporal correlation (art. 6) and geographical correlation (art. 7). Additionally, there are exemptions attributed to specific grid conditions that allow for the electricity taken from the grid to be counted as fully renewable.

Table 1 gives an overview of the possible sourcing pathways under DA 1184 and their respective requirements applicability.

Table 1: Requirements overview on fully renewable electricity sourcing pathways covered by DA 1184. Table based on (ISCC, 2025a)

	<i>Direct connection</i>	<i>Grid Connection</i>			
		>90% RES	<18 gCO ₂ eq/MJ	Imbalance settlement period	Electricity from the grid with requirements
Additionality	✓*	✗	✗	✗	✓**
Temporal correlation	✗	✗	✓	✗	✓
Geographical correlation	✗	✗	✓	✗	✓
Renewable PPA	✗	✗	✓	✗	✓

* 36 months

** 36 months (transition period criteria applicable to plant installed by 01.01.2028), no operating or investment aid

Bidding Zone with more than 90% Renewable Share

An RFNBO producer may consider grid electricity as fully renewable if the RFNBO producing plant is located in a bidding zone where the average renewable electricity share exceeded 90% in the previous year. In this case, RFNBO production is permitted only up to a number of full load hours equivalent to that renewable share. Any production beyond this limit is not considered renewable. Once the 90% threshold is met, it is deemed to remain above 90% for the following five years.

The 90% rule offers simplified compliance, as hourly granularity of renewable and grid electricity scouring is no longer necessary. For this reason, it will not be considered in the model developed in this thesis, which focuses on hourly precision and temporal correlation.

Bidding Zone with less than 18 gCO₂eq/MJ

When the installation producing RFNBO is located in a bidding zone with a carbon intensity lower than 18 gCO₂eq/MJ, the electricity taken from the grid may be counted as fully renewable when the following criteria are met:

- The fuel producer concluded a renewable PPA directly or through intermediaries, with an economic operator of an installation producing renewable electricity for an amount equal to or lower than the electricity being generated from the installation.
- The conditions on temporal and geographical correlation in accordance with Chapters 3.2.2 and 3.2.3 are met.

It is assumed that since the bidding zone already has low carbon emissions from electricity production, usually due to a high share of nuclear power, further decarbonisation through

additional renewable electricity installations is not necessarily required. The additionality requirement can therefore be waived (Hydrogen Europe aisbl, 2023). Once a bidding zone shows emissions of less than 18 gCO₂eq/MJ, it shall be assumed so for the next five years.

With respect to the model, as with the supply via direct connection, no additional constraints can be concluded other than those already considered under chapter 3.2. However, the techno-economic benefit of not having to solely rely on electricity sourcing from additionality compliant RES, should not be neglected and will be discussed in chapter 4.1.

Imbalance Settlement Period

Electricity consumed during imbalance settlement periods can be counted as fully renewable if the RFNBO producer can demonstrate that its consumption directly reduced the need for downward redispatch actions by the TSO. However, proving causality requires access to real-time data on redispatch events within the bidding zone, which is currently not publicly available.

Germany is actively exploring a solution for this through a pilot mechanism introduced in §13k of the Energy Industry Act (EnWG). This provision establishes a market-based system whereby registered flexible consumers such as electrolyser operators can bid to absorb otherwise curtailed renewable electricity at potentially very low or zero cost. The initiative, known informally as "Nutzen statt Abregeln", is currently undergoing a two-year trial phase in selected regions, after which it will be evaluated and potentially scaled up (BNetzA, 2024a).

Due to the current regulatory uncertainty, the limited geographical coverage and the lack of operational transparency or real-time redispatch data, many project developers remain cautious on relying on this pathway for RFNBO compliance. Therefore, electricity sourcing during imbalance settlement periods will not be considered in the simulations.

3.2 Compliance Requirements for Grid-Connected RFNBO Production

For electricity taken from the grid that does not fall under the exemptions outlined in Chapter 3.1.3, specific requirements must be met for the electricity to qualify as fully renewable. This applies when the RFNBO production is located in a bidding zone where the share of renewables is below 90% and the carbon intensity is above 18 gCO₂eq/MJ. In such cases, a renewable PPA must be in place. As previously described for electricity supplied in decarbonized grids (<18 gCO₂eq/MJ), this PPA serves to demonstrate compliance with the principles of additionality, temporal correlation and geographical correlation. These criteria must be verified by an auditor as part of the RFNBO certification process.

3.2.1 Additionality

The additionality condition (DA 1184 Art. 5) states that any electricity drawn from a renewable PPA must originate from RES that have come into operation not earlier than 36 months prior to the installation producing RFNBO. It is to be ensured that the RES has either not received or paid back in full, any and all operating or investment state aid including feed-in tariffs.

A transitional phase on compliance with the additionality condition was added in Art. 11 DA 1184, to ensure that projects under advanced development are considered fairly. For all RFNBO producing capacity that will come into operation before 01.01.2028, the compliance requirement is postponed until 01.01.2038. Figure 4 shows how additionality and the transitional phase on the condition affect the range of potentially ‘usable’ RES capacity for electrolyzers with commercial operation dates (COD) before and after 01.01.2028. The orange area represents the usable RES capacity for ‘Electrolyzer 1’ (EL 1) that has come into operation without having to comply with additionality, while the blue area shows the same for ‘Electrolyzer 2’ (EL 2), having to comply with the 36-month window under additionality.

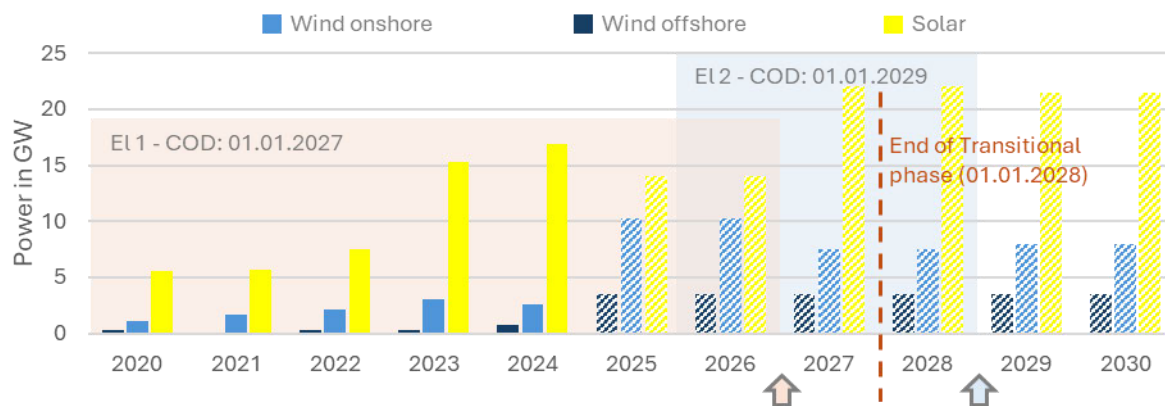


Figure 4: Usable RES depending on COD of electrolysis capacity installed in Germany, considering the transitional phase on additionality. Historical data until 2024 for annual added net RES capacity (solid bars) taken from energy charts (Energy Charts, 2025). Projected data (hatched bars) based on RES capacity targets formulated under EEG 2023 § 2 and WindSeeG § 1.

The additionality condition will be considered in the model by assuming appropriate electricity costs for RES in line with the respective planned COD. Electricity cost will depend on the bidding zone specific market on long term PPAs. This will be further discussed in chapter 4.1.

3.2.2 Temporal Correlation

Temporal correlation means that electricity supplied under a renewable PPA can only be counted as fully renewable if it is consumed at the RFNBO producing plant within the same pre-determined time window. Initially this will be on a monthly basis (monthly correlation), but from 01.01.2030 it will be on an hourly basis (hourly correlation).

Figure 5 shows how economic operators can optimize the consumption of electricity produced from the PPA at the spot market under monthly correlation. Electricity produced from the renewable PPA that surpasses the maximum possible uptake at the plant can be sold off. When there is low or no production from the contracted RES, additional electricity can be taken from the grid and claimed as fully renewable using the positive balance of retained guarantees of origin (GoO).

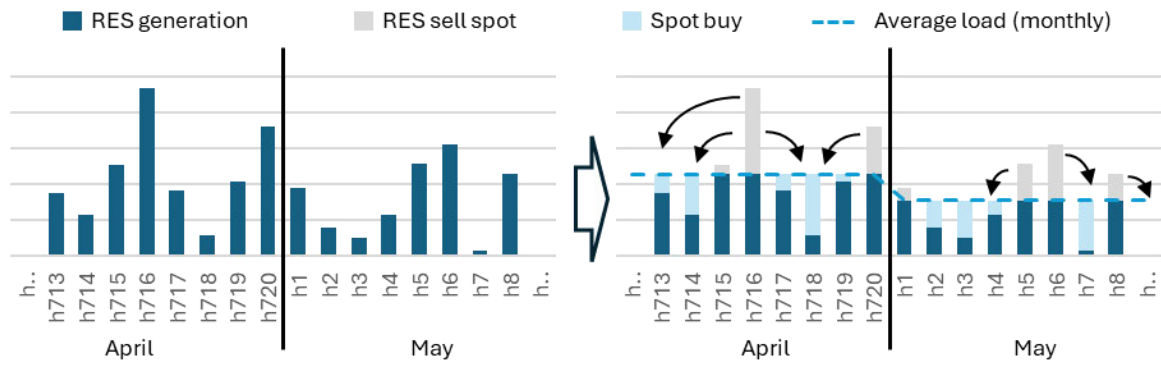


Figure 5: Peak shifting through spot market optimization under monthly correlation

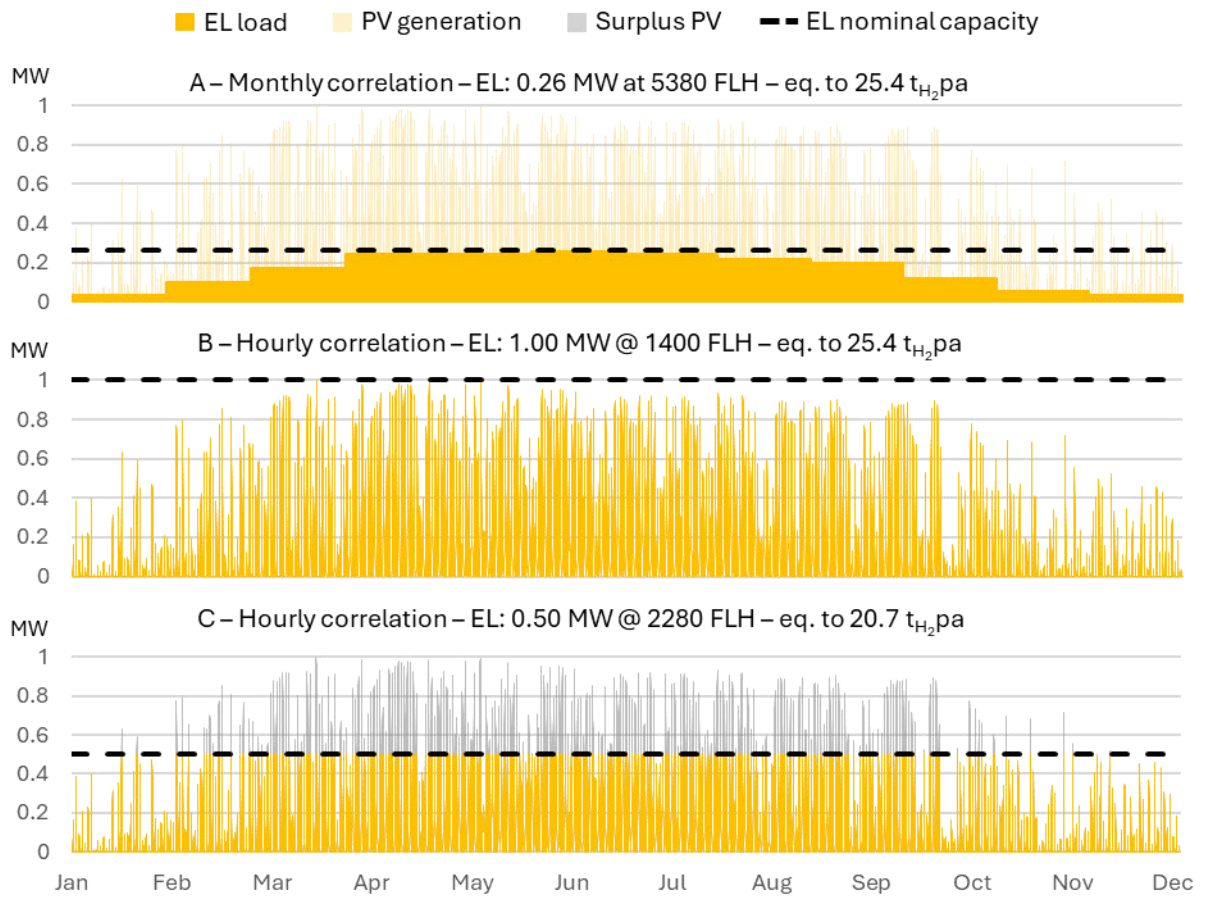


Figure 6: Electrolyzer (EL) utilization and expected annual yield assuming 55 MWh/t_{H2} for (A) 0.26 MW_{el} EL following monthly correlation, (B) 1 MW_{el} EL and (C) 0.5 MW_{el} EL following hourly correlation. (A), (B) and (C) supplied by the same 1 MW_p PV installation operating at 1400 FLH taken from ("Renewables.ninja," n.d.).

The impact of monthly and hourly correlation on RFNBO plant utilization and resulting expected yield is visualized in Figure 6. Three electrolyzers of different capacity are supplied by the same 1 MW_p PV RES. Through peak-shifting under monthly correlation, as depicted in Figure 5, it would be possible to utilize the entire electricity generated from the PV RES in a 0.26 MW electrolyzer operating at 5280 FLH, resulting in an equivalent annual H₂ production of 25.4 t_{H2}pa (A). To achieve the same yield under hourly correlation, it would require an

electrolyzer scaled to 1:1 to the PV RES (B), that would subsequently show the same utilization of 1400 FLH as the PV RES. This is irrespective of minimum turndown constraints of the electrolyzer, so in practice utilization would be even lower. Low utilization on the electrolyzer increases the relative cost contribution of investment cost for the electrolyzer on the overall product price. To increase utilization on the electrolyzer the power ratio between PV RES and electrolyzer would have to be increased as shown in (C). This results in lower annual yield, since surplus generation from PV RES would have to be either curtailed or sold off at the spot market. BESS capacity could also be added to reduce surplus/curtailment. Plants operating under hourly correlation need to strike a balance between oversizing and diversifying RES sources, adding storage capacities and sizing of electrolyzer capacity, in order to achieve lower RFNBO production cost.

Temporal correlation under DA 1184 Art. 6 also puts restrictions on the use of BESS. Electricity discharged from a BESS and used to produce RFNBOs can only be considered fully renewable, if the BESS was charged during the same hour or month in which the electricity was generated by the RES covered under the PPA. Additionally, the BESS must be located behind the same metering point as either the plant procuring RFNBO or the RES, meaning that electricity drawn from i.e. a grid stabilizing BESS connected somewhere else to the grid, cannot be considered fully renewable.

Other than with the additionality condition, there is no prolonged leniency on the temporal correlation requirement for RFNBO producing installation that have come into operation until a specific date. This means the later a RFNBO producing plant comes into operation, the shorter the timespan in which it can be operated under monthly correlation – if at all. As indicated earlier, monthly and hourly correlation pose different options and risks on the procurement strategy for electricity, that may conclude in vastly different RES portfolios. From a project finance perspective, where long-term stability and risk mitigation are essential, this regulatory shift presents a structural challenge (Yescombe, 2014, chap. 9). Switching between monthly and hourly correlation is not only impractical, but it also undermines the ability to build a robust electricity sourcing strategy based on predictable cost structures. The electricity sourcing strategy, particularly the use of long-term pay-as-produced PPAs, will be discussed further in Chapter 4.1.

Hourly correlation will therefore be considered as the baseline during the planning and financing stage and will be implemented as such in the simulation model of this thesis. While temporary relief from monthly correlation may offer some operational flexibility early on, it will be treated as a bonus rather than a design assumption and will subsequently not be considered in the model.

3.2.3 Geographical Correlation

The condition on geographical correlation (DA 1184 Art. 7) demands that the installation producing RFNBO and the RES supplying it under a renewable PPA must be in the same bidding zone, or an interconnected offshore bidding zone at the time of COD. When located in a neighbouring bidding zone, electricity supplied from the RES may only be counted as fully renewable

during hours where the day-ahead price in the neighbouring bidding zone is equal or lower than in the bidding zone where the RFNBO is produced.

For simplification it will always be assumed, that RES and RFNBO plant are either in the same bidding zone or an interconnected offshore bidding zone.

3.3 GHG Emission Intensity Threshold and Accounting

3.3.1 RFNBO Chain of Custody and Traceability

According to revised directive EU/2018/2001, economic operators shall provide evidence that the sustainability and GHG savings criteria have been fulfilled. Voluntary schemes, such as CertifHy, introduce a system of measures and requirements to ensure traceability of produced products. The aim is to be able to identify and trace the origin, processing history, distribution and location of products as well as materials through supply chains.

Thus, the traceability and evidence of the sustainability characteristics of products are achieved by applying traceability measures. To do so, a chain of custody system must be implemented that allows the economic operator to trace sustainability and GHG saving attributes of certified products, based on the mass balance method, through the processes included in the scope of certification. A mass balance system allows the physical mixing of fuels and materials with different sustainability and GHG emissions saving characteristics and non-renewable fuels and materials. The information about the sustainability characteristics and size of consignments with differing sustainability and GHG emissions saving characteristics must remain assigned to the mixture.

Every economic operator along RFNBO supply chain must be certified, starting with the RFNBO producer and ending with the last economic operator handing over the RFNBO to the end user. Each operator must account for upstream emissions (e_{up}) including transport and their own processing emissions, with the final supplier additionally accounting for the downstream emissions (e_{down}) including combustion emissions from use (see Table 2).

Table 2: Relevant supply chain elements for calculation (CertifHy, 2024)

<i>First processing unit (hydrogen production or in- tegrated RFNBO production)</i>	<i>Further processing units and/ or storage</i>	<i>Final processing unit and/ or storage</i>
Processing emissions	Processing emissions	Processing emissions
Upstream emissions (e_{up}) (electricity, CO ₂ , water, etc.) incl. transport	Upstream emissions (e_{up}) incl. transport	Upstream and downstream emissions ($e_{up} + e_{down}$) incl. transport

Proof of the sustainability (PoS) characteristics of an RFNBO is documented and communicated through the supply chain using a PoS which is always linked to a specific product batch.

A PoS is a delivery document containing relevant information about the RFNBOs that must be issued by the supplier for each delivery of RFNBO volumes.

While each economic operator is responsible for their process related emissions, only RFNBO that fulfils the 70% emissions saving target across the entire relevant supply chain can be used by obligated parties to fulfil their fuel specific targets, imposed on member state level under REDII. In practice this means, that economic operators further down the supply chain may impose limits on upstream emissions for fuel delivered from their RFNBO suppliers, ensuring that after considering their own processing and downstream emissions, the fuel still qualifies as a compliant RFNBO.

The scope of the model reflects the system boundary of an RFNBO fuel producer as defined under the REDII and the DAs. Specifically, the model represents a production site supplying RFNBO-compliant ammonia at the point of dispatch (Ex Works). The model shall therefore only consider upstream emissions from inputs supplied to the RFNBO production and emissions from processing onsite. While downstream emissions will not be considered in the model, a variable GHG emission limit, lower than that required to fulfil 70% GHG saving, shall be implemented to more accurately mirror the actual RFNBO supply chain requirements.

3.3.2 Methodology to Determine GHG Savings for RFNBO

To assess the sustainability characteristics for the PoS, the DA 1185 outlines a methodology to calculate the GHG savings associated with RFNBO production in accordance with the requirements defined in the REDII.

Emissions must be accounted for in a ‘well-to-grave’ approach. Compared to a ‘cradle-to-grave’ approach, upstream emissions for manufacturing of machinery and equipment are excluded (DA 1185 Annex A 1.). GHG emissions assigned to a production batch must be stated in gCO₂eq/MJ, referring to the total emissions accounted for the batch of fuel divided by its energy content, assuming the lower heating value of the fuel. Emissions must be given in CO₂ equivalents (gCO₂eq), so that not only emissions from CO₂, but other, more potent greenhouse gases are also included in the life cycle emissions of the produced RFNBO. The relevant greenhouse gases are CO₂, CH₄, and N₂O, with their respective associated global warming potentials (GWP) of 1, 25, and 298 according to REDII Annex V C. point 4. Gaseous hydrogen emissions from processing (i.e. Haber-Bosch purge gas) or H₂ storage slip are not yet included in the regulations and are therefore only accounted for in energy losses (ISCC, 2025b).

To determine the total emissions from the use of RFNBO fuel (10) and the corresponding GHG emission saving against a fossil fuel comparator (11), the following calculations must be applied (DA 1185 Annex A. 1 & 2):

$$E = e_i + e_p + e_{td} + e_u - e_{ccs} \quad (10)$$

$$Savings = (E_F - E) / E_F \quad (11)$$

where:

E = total emissions from the use of the fuel (gCO₂eq/MJ fuel)

$E_F =$	total emissions from the fossil fuel comparator that shall always be 94 gCO ₂ eq/MJ fuel
$e_i =$	$e_i \text{ elastic} + e_i \text{ rigid} - e \text{ ex-use}$: emissions from supply of inputs
$e_i \text{ elastic} =$	emissions from elastic inputs; elastic inputs are those whose supply can be increased to meet extra demand
$e_i \text{ rigid} =$	emissions from rigid inputs; rigid inputs are those whose supply cannot be expanded to meet extra demand
$e \text{ ex-use} =$	emissions from inputs' existing use or fate include all emissions in the existing use or fate of the input that are avoided when the input is used for fuel production (CO ₂ input from an eligible source that is chemically incorporated into carbon based RFNBOs)
$e_p =$	emissions from processing shall include direct atmospheric emissions from the processing itself, from waste treatment and leakages
$e_{td} =$	emissions from transport and distribution shall include emissions from the storage and distribution of the finished fuels. Emissions attributed to inputs e_i shall include emissions from their associated transport and storage
$e_u =$	emissions from combusting the fuel in its end-use
$e_{CCS} =$	emission savings from carbon capture and geological storage

To determine the GHG emissions threshold for compliant RFNBO, equation (11) can be solved for E , then entering 70% GHG saving and 94 gCO₂eq/MJ for the fossil fuel comparator into the new formula, resulting in 28.2 gCO₂eq/MJ fuel¹. This means only fuel with well-to-grave emissions lower than 28.2 gCO₂eq/MJ fuel is considered compliant RFNBO and can be used to fulfil target obligations set out under REDII, its revisions and national implementations. Anything above will lose the fuel its RFNBO qualification, rendering it useless for target fulfilment and subsequently losing its economic premium on the market. As production costs remain, it should be in the best interest of fuel producers to achieve a low enough fuel carbon intensity to ensure RFNBO compliance.

To determine the carbon intensity over the entire RFNBO production process, each processing step must assess its emissions contribution to the final product.

- Where elastic inputs are obtained from incorporated processes, GHG emissions shall be determined based on data from their actual production process (DA 1185 Annex A 7.). Hydrogen for instance is obtained from an incorporated process (electrolysis) and is an elastic input to the storage compressor and the Haber-Bosch process.
- Where inputs are supplied from external parties, input specific emissions shall be taken from part B of the annex. For inputs that are not included in part B, the fuel supplier

¹ $E = E_F (1 - \text{savings}) = 94 (1 - 0.7) = 28.2 \text{ gCO}_2\text{eq/MJ fuel}$

shall apply the same methodology listed in DA 1185 to determine the inputs' specific emissions intensity.

As mentioned in chapter 3.1, fully renewable electricity used as an input to produce RFNBO is accounted for with zero gCO₂eq/MJ in the emission calculation.

Where electricity qualifying as fully renewable is used as an input that enhances the heating value of the fuel or intermediate products (electrolysis), the GHG emission intensity must be calculated in a time interval that is in line with the requirements applying for temporal correlation (DA 1185 Annex A 1.). This means that in the model the GHG emission intensities shall be calculated on an hourly basis, in line with the hourly correlation derived in chapter 3.2.2.

Processes within the RFNBO production, which do not increase the heating value(s) of its input(s), may use electricity that does not qualify as fully renewable. DA 1185 Annex A 6. introduces three alternative methods to determine specific emissions of electricity taken from the grid, that does not qualify as fully renewable, used in the production of RFNBO. Methods may be changed throughout the operational lifetime of production, but cannot be changed within a running calendar year.

- a) Emissions from grid electricity may be assessed on country or bidding zone level according to DA 1185 Annex C, provided that reliable data is available.
- b) Emissions can also be assigned based on the number of full load hours the RFNBO-producing installation operates. If the full load hours are equal to or fewer than the total hours during which the marginal electricity price was set by renewable or nuclear sources in the previous calendar year (for which reliable data is available), then the grid electricity used may be considered with 0 gCO₂eq/MJ. However, if the installation operates beyond this threshold, the grid electricity consumed must be assigned a GHG emissions value of 183 gCO₂eq/MJ.
- c) Alternatively, emissions can be calculated based on the GHG intensity of the marginal electricity-generating unit at the time of RFNBO production within the relevant bidding zone, provided this information is publicly available from the TSO.

If the method set in point b) is used, it shall also be applied to electricity that is used to produce RFNBO and that qualifies as fully renewable.

In general, point b) and c) are of less importance for RFNBO production. Both methods focus on ensuring zero or low emissions for electricity sourced from the grid, rather than on establishing the direct temporal correlation with renewable generation required under RFNBO criteria. As such, they are more aligned with low-carbon hydrogen or ammonia certification schemes, which allow for average or marginal emission-based accounting. Consequently, methods b) and c) are not considered in this work.

For method a), assessment on bidding zone level may yield lower specific grid emissions than on country level. In France for instance, grid emissions at country level were at 19.6 gCO₂eq/MJ for 2020 (DA 1185 Annex C. table A), compared to 15.1 gCO₂eq/MJ on bidding zone level for mainland France. This can be attributed to high emissions in French overseas territories, inflating the emissions on country level (Hydrogen Europe aisbl, 2023). In this case the benefit of assessing emissions on bidding zone level would be substantial, as grid

emissions are below 18 gCO₂eq/MJ and thereby decarbonized, alleviating RFNBO producers from the additionality requirement.

For simplification purposes, the model shall abide by method a) on country level. Specific grid emissions for EU member states are provided in Table A of DA 1185 Annex C. These values will be regularly updated and published by the Joint Research Centre (JRC), with the latest values published in 2024 for the years until 2022 (Bastos et al., 2024). Within the model, processing steps that do not increase the heating value of the product shall be permitted to use grid electricity, provided that the total greenhouse gas emissions of the final ammonia product remain below the regulatory threshold.

3.3.3 Emission Allocation in Storage

The treatment of energy and emissions during storage is a critical component of compliance with the RED II DAs. In this context, storage systems used within the P2A process must maintain the integrity of both mass and emission balances, ensuring traceability and regulatory alignment.

For storing electrical energy in a BESS, the implementation in the model is clear. It is to be ensured, that only fully renewable electricity from the PPA is stored in the BESS. Thereby average specific emissions are always zero. Electricity can be discharged irrespective of when it has been charged.

In contrast, the emission allocation methodology for hydrogen storage is more complex. Both the RED II DAs and voluntary scheme documentations (ISCC, CertifHy) do not explicitly prescribe emission handling for hydrogen stored over time. Nonetheless, compliance with the principles of hourly correlation and mass balance must be ensured. This implies that batch-level tracking is required. Every hydrogen batch entering storage must retain its time stamp, production quantity and associated carbon intensity. This includes compression emissions that are only accounted to hydrogen differed to the H₂ storage tank. These emissions could arise when compressors are powered by grid electricity rather than RE from RES. Depending on specific compression demands and grid carbon intensity, the carbon intensity of the hydrogen can increase beyond the RFNBO threshold of 28.2 gCO₂eq/MJ, resulting in batches of non-compliant RFNBO stored hydrogen. During downstream processing in the Haber-Bosch, non-compliant RFNBO batches used from storage would form a mixture with RFNBO hydrogen directly fed from the electrolyzer. According to mass balance rules, emissions from both streams of RFNBO (compliant and non-compliant) would be averaged to form the specific emission intensity of the hydrogen mixture fed into the Haber-Bosch process. As the simulation results shall yield 100% RFNBO compliant ammonia, the RFNBO input mixture must not exceed a permissible average carbon intensity that allows for the RFNBO ammonia to remain below the regulatory compliance threshold.

To uphold traceability requirements across the entire P2A process, a batch and emissions handling system for hydrogen storage must be included in the model. Given the need for both simplicity and regulatory conformity, the model shall adopt a first-in, first-out (FIFO) approach for hydrogen storage. Under FIFO, hydrogen is withdrawn in the chronological order in which it was stored, preserving batch integrity and simplifying traceability. Each batch retains its

original timestamp and carbon intensity. The average carbon intensity of the hydrogen used at any given time can therefore be determined based on the specific mix of stored hydrogen withdrawals and newly produced hydrogen from electrolysis.

3.4 Summary of Derived Simulation Constraints

This section consolidates the regulatory obligations relevant to RFNBO ammonia production under the RED II and its DAs. To ensure compliance within the simulation model, these provisions are translated into a structured set of modelling constraints. Table 3 below summarizes these regulatory requirements and formulates them as simulation demands, which will guide the implementation of the computational logic in Chapter 5. Technical process constraints and design assumptions beyond the legal scope are discussed separately in Chapter 4.

Table 3: Overview of regulatory constraints derived from RED II and its delegated acts, translated into corresponding simulation demands to ensure RFNBO compliance within the modelling framework

<i>Legal basis</i>	<i>Regulatory requirement</i>	<i>Simulation constraint / demand</i>
DA 1184 Art. 6	Hourly correlation: Electricity used for RFNBO production must originate from RES generation within the same hour	Electricity used for hydrogen production must be matched with renewable generation on an hourly basis
DA 1184 Art. 7	Geographical correlation: RES and RFNBO plant must be in the same or interconnected bidding zone	Only RES profiles from the same bidding zone as the plant are eligible as inputs
DA 1184 Art. 5 + Art. 11	Additionality: RES must be newly commissioned (≤ 36 months before RFNBO plant COD), unless in transition period	Only newly built RES are eligible post-2028. The model must ensure RES commissioning dates align with REDII timelines
DA 1185 Annex A.5	Fully renewable RES: fully renewable RES electricity has CI = 0 gCO ₂ eq/MJ	All electricity from compliant RES carries zero emissions
RED II Art. 25 (2) DA 1185 Annex A.1 + 2	GHG intensity threshold: RFNBO fuel must not exceed 28.2 gCO ₂ eq/MJ	Model must calculate well-to-grave emissions of ammonia and verify that values remain below 28.2 gCO ₂ eq/MJ Implement variable emissions threshold to consider constant processing and other downstream emissions
DA 1185 Annex A. 7 + 8	Full life-cycle accounting: GHG emissions from all processing steps and external suppliers must be included	The carbon intensity of each processing step must be calculated individually and aggregated. Emissions from upstream suppliers must be assigned accordingly
DA 1185 Annex A. 6	Grid electricity accounting: For non-heating-value-increasing steps, country-average grid CI is permitted	Grid electricity may be used for auxiliary steps (e.g. compression), provided it does not cause the product's total emissions to exceed the GHG

<i>Legal basis</i>	<i>Regulatory requirement</i>	<i>Simulation constraint / demand</i>
		threshold. Country-specific CI factors from JRC shall be applied
RED II Art. 30	Traceability and chain of custody: Input emissions and origin must be trackable per batch	Model must assign timestamps and carbon intensity to all electricity and H ₂ inputs to ensure traceability of ammonia emissions
		The simulation must model hydrogen storage with batch-level CI assignment and first-in-first-out (FIFO) or equivalent logic for downstream CI propagation

4 Techno–Economic Analysis

This chapter provides a techno-economic analysis of P2A systems under RFNBO compliance constraints. It outlines the key technical parameters, system components and cost-driving factors that influence the feasibility of ammonia production powered by renewable electricity. The goal is to define realistic boundary conditions and model assumptions based on existing literature and industrial data. These form the basis for the simulation model developed in the subsequent chapter.

4.1 Electricity Supply

The following section focuses on the electricity supply options considered for the P2A system. It compares renewable electricity procurement via PPAs with grid electricity, evaluating their respective techno-economic and regulatory implications. Key metrics such as full load hours, price structures and carbon intensities are discussed to assess their impact on both system performance and REDII compliance.

4.1.1 Renewable Electricity via PPA

Hourly Renewable Generation Data

A key requirement in the simulation of RFNBO-compliant ammonia production is the availability of high-resolution, hourly renewable generation data. This data must accurately reflect the temporal dynamics of the renewable supply to ensure regulatory conformity, particularly with respect to the hourly correlation criterion outlined in chapter 3.2.2.

There are various approaches to derive such hourly generation profiles. One option is to use historically measured generation data for specific locations, provided by RES developers or economic operators during the negotiation of offtake agreements. These datasets typically reflect real asset performance and are therefore highly representative of actual site conditions.

In cases where direct measurements are unavailable, standardized generation profiles may be used. A simplified, but illustrative method involves constructing PV output profiles by combining a cropped sine wave with a superimposed seasonal sine function to account for seasonal changes. This method, while analytically convenient, has been shown to inadequately represent the variability and intermittency observed in real-world operations (Smith and Torrente-Murciano, 2024).

A widely adopted method involves the use of synthetic profiles generated through meteorological reanalysis data combined with renewable energy system models. In this thesis, time series for both solar and wind energy are generated using the open-source platform Renewables.ninja. This tool has been applied in a range of comparable studies (Campion et al., 2023;

Ishaq et al., 2023; Verleysen et al., 2023a) and is suitable for generating long-term, hourly-resolution renewable profiles. Renewables.ninja utilizes meteorological inputs from global re-analysis models and satellite observations. For wind energy, the NASA MERRA-2 dataset provides the necessary wind speed data, while solar irradiance is derived from the CM-SAF SA-RAH dataset. Conversion from meteorological variables to electricity output is performed using technology-specific models: the Global Solar Energy Estimator (GSEE) for PV and the Virtual Wind Farm (VWF) model for wind energy (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016).

While this approach captures hourly and seasonal variability effectively, it is important to note that long-term interannual fluctuations in resource availability are not explicitly addressed within this thesis. In practice, such variations are often accounted for through Pxx-yield analysis (e.g., P50, P75, P90), which quantifies the statistical likelihood of generation under different conditions. Although such assessments are essential in project finance and risk evaluation contexts, they are beyond the scope of this work and are only acknowledged here for completeness.

Electricity Cost for Renewable PPAs

The levelized cost of electricity (LCOE) from renewable sources is a central determinant in the economic performance of RFNBO systems. For wind and PV, LCOE is primarily driven by resource availability (i.e. wind speed distributions and global horizontal irradiance), capital expenditures and plant lifetime, with operational costs playing a minor role (Kost et al., 2024). BESS are increasingly integrated, influencing system flexibility and cost.

From a project finance perspective, long-term price stability is essential for both investors and offtakers in renewable energy projects. PPAs are the predominant contractual instrument used to secure such stability.

In the context of RFNBO production, the contractual structure of PPAs is required to source fully renewable electricity under DA 1184. To meet the criterion of hourly correlation between renewable electricity generation and hydrogen production, only a specific subset of PPA structures is suitable. Pay-as-produced, in which the offtaker receives the physical electricity output as it is generated in real time, are effectively the only arrangement capable of ensuring compliance with this requirement. These contracts are analogous to feed-in tariffs under the German Renewable Energy Act (EEG).

By contrast, structured portfolio-based PPAs, which often involve financial hedging, volume shaping and spot market optimization, do not guarantee a temporal match between generation and consumption. Any shortfall in RES generation is typically compensated with electricity from the public grid, which may not qualify as fully renewable under DA requirements. This can lead to periods of non-compliant RFNBO production, which is not the scope of the model in this thesis. Therefore, in the context of RFNBO plant design, the use of structured PPAs poses a compliance risk and is excluded from further consideration in this thesis.

Further constraints arise from the additionality requirement as described in chapter 3.2.1. Only RES assets that have come into operation no more than 36 months before the commissioning date of the RFNBO plant are considered eligible. Additionally, these assets must not have

benefited from operating aid such as fixed feed-in tariffs. As a result, only newly built renewable energy assets qualify under the regulation, effectively narrowing the pool of available supply and reinforcing the need for bilateral, market-based offtake agreements. These agreements are negotiated outside of public support schemes under "Direktvermarktung" terms in Germany.

This shift imposes significant project-on-project risk: both the renewable generator and the ammonia producer become mutually dependent on each other's successful realization. RES developers opting to forego guaranteed EEG-backed revenue streams must be compensated with risk-adjusted PPA pricing, likely to include a premium to reflect uncertainties in project co-development. This risk premium, while challenging to quantify, is a critical consideration in early-stage financial modelling.

Subsequently, the effective benchmark for minimum fixed electricity price for pay-as-produced PPA in Germany are the clearing prices of EEG tender rounds administered by the Federal Network Agency (BNetzA). While the nominal ceiling for bid prices in 2023 was 5.88 ct/kWh (EEG §36b), this cap is subject to annual reductions of 2% beginning in 2025. However, due to under-signing of tender volumes in recent years, price ceilings have been lifted (BNetzA, 2024b). Figure 7 shows clearing prices for onshore wind and ground-mounted PV tenders over the last years, with clearing prices for wind around 6 to 7 ct/kWh and PV around 5 ct/kWh.

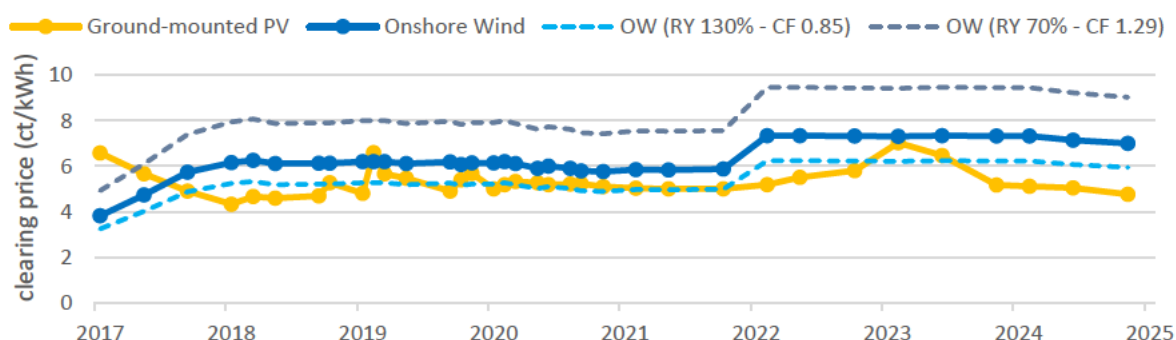


Figure 7: Clearing price history for PV and onshore-wind tenders. Dashed lines show effective awarded prices for reference yield model evaluations (RY) of 130% & 70% and resulting scaled clearing price with correction factor (CF) 0.85 & 1.29 (EEG § 36h). Data taken from (BNetzA, n.d.)

An additional complexity arises from the location-specific adjustment mechanism outlined in EEG §36h. This framework was introduced to incentivize wind development in southern Germany, where resource availability is lower, but consumption is high. Feed-in tariffs awarded to onshore wind installations are adjusted according to a reference yield model, with sites falling below 50% of the reference yield receiving up to a 55% increase in awarded tariffs via a correction factor. While this policy seeks to balance grid congestion and load centres, it also reduces the competitiveness of high-yield sites within the EEG system.

Consequently, wind projects located in resource-rich areas, such as northern Germany, may increasingly opt out of EEG tenders and turn to the free market, including direct PPAs with industrial offtakers. This could improve availability and potentially lower prices for high-quality, grid-competitive renewable electricity suitable for RFNBO applications.

In the simulation model developed in this thesis, PPA-based electricity prices for wind and solar PV are treated as input parameters. Default values reflect recent EEG tender outcomes and publicly available project benchmarks for Germany. These inputs can be modified to reflect specific locational contexts or future cost developments. All scenarios assume pay-as-produced PPAs, ensuring strict compliance with the hourly correlation requirement and avoiding the risk of partial non-RFNBO output.

Reference PPA RES Assets

To analyse the impact of renewable energy availability on P2A plant performance, four representative RES profiles were selected using data from Renewables.ninja. The profiles are categorized as “high” and “low” based on 20-year average annual full load hours (FLH). They represent typical wind and PV conditions within Germany (Kost et al., 2024). The following table summarizes the selected reference sites and their corresponding FLH values. Additional analysis and data on the reference RES assets are provided in Appendix B.

Table 4: FLH analysis of 20-year RES time series data with pay-as-produce PPA electricity price assumptions used in this thesis

Type	Quality	Location	Annual FLH					Fixed pay-as-produce PPA price (EUR/MWh)
			Mean	Median	StdDev	Max	Min	
PV	Low	DE-NS	1090	1092	36	1164	1020	50
	High	DE-BY	1297	1295	45	1416	1216	45
Wind	Low	DE-BY	1875	1866	146	2266	1640	90
	High	DE-SH	3504	3537	142	3737	3274	65

4.1.2 Grid Electricity Consideration

Spot Market Pricing

The integration of grid electricity into P2A systems introduces both operational flexibility and economic uncertainty. To evaluate its impact in a techno-economic framework, the treatment of spot market electricity pricing must avoid artificial correlations with renewable output patterns that would distort model outcomes.

While some studies, such as Salmon and Bañares-Alcántara (2021), have relied on hourly historical pricing data to simulate grid electricity prices, this thesis adopts a simplified but robust approach. Two static prices are assumed: one for purchasing electricity from the grid and one for selling surplus electricity to the grid. This avoids parasitic alignment between renewable generation and electricity cost, which could emerge if time-coupled pricing data were used. Unlike Wu et al. (2024), who applied a uniform price for both grid transactions, this model treats buying and selling prices independently.

These fixed prices are based on the typical conditions under which grid interactions occur in a RES supplied P2A system. Electricity is purchased in hours of low RES output, to sustain

electrolyzer operation or to meet the minimum load requirements of the Haber-Bosch synthesis loop. Conversely, electricity is sold when PPA-based renewable production exceeds internal demand and storage is saturated.

However, renewable output is not independent of wider market dynamics. Especially in PV-integrated systems, RES production typically peaks during midday, when spot prices tend to fall. This effect is illustrated in Figure 8, which shows hourly renewable and non-renewable production alongside day-ahead auction prices for March 2025 in the DE-LU bidding zone. A clear negative correlation is visible: as renewable output rises, day-ahead prices drop.

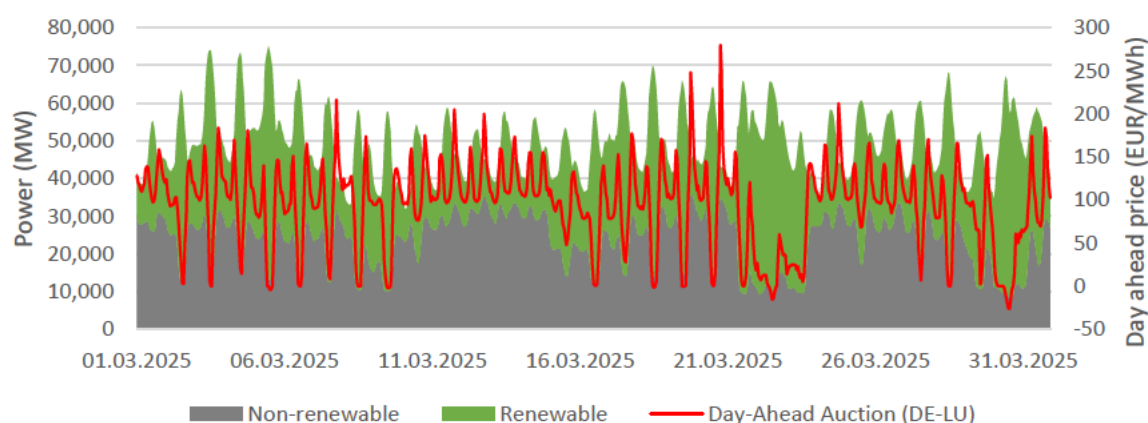


Figure 8: Electricity production from renewable and non-renewable sources together with day-ahead auction results in the DE-LU bidding zone for march of 2025 (Data from Energy-Charts.info)

This dynamic is further evidenced by the increasing frequency of negative day-ahead prices in recent years, shown in Figure 9. Between 2022 and 2025, the number of hours with negative prices has risen sharply, particularly in late spring and summer. These instances coincide with periods of high renewable generation and insufficient demand, reinforcing the structural price suppression during surplus RES conditions.

Accordingly, expected revenues from surplus electricity sales in P2A systems should be significantly reduced compared to average spot prices. In contrast, electricity purchases typically occur during low-RES hours, when market prices are elevated. Therefore, the assumed average grid electricity purchase price should exceed the average selling price to realistically reflect market asymmetries. Both sales and purchasing price will be considered conservatively with 0 and 150 EUR/MWh, respectively.

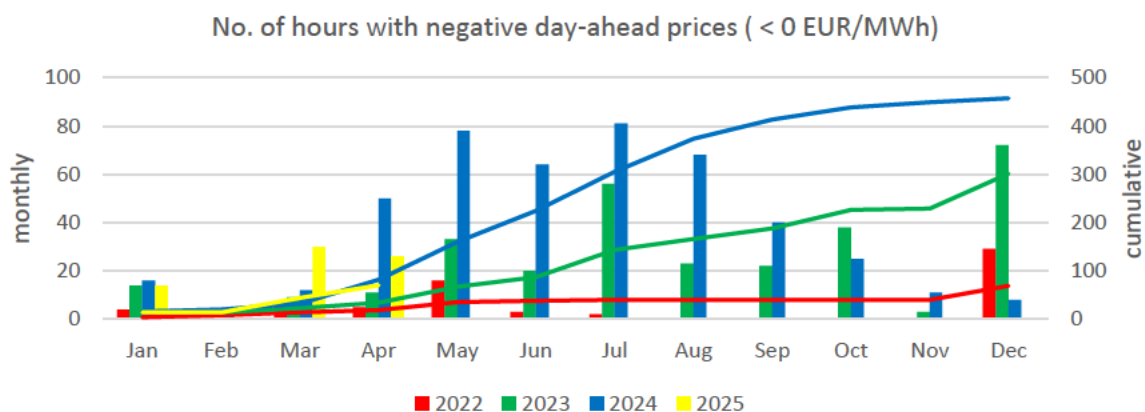


Figure 9: Development of negative day ahead prices from 2022 to 2025. Figure updated from (WD 5 - Deutscher Bundestag, 2024) using latest data from energy-charts.info

Renewable Share and Carbon Intensity

In addition to electricity prices, the sustainability characteristics of grid electricity, particularly its renewable share and carbon intensity (CI), are critical parameters for assessing the regulatory feasibility of RFNBO production. As with price developments, these characteristics are difficult to forecast. Their evolution depends on the specific national strategies adopted by member states in response to overarching EU climate targets.

Official statistics on grid sustainability are published regularly by the European Commission, primarily through Eurostat's SHARES Tool (Eurostat Database, 2025) and the JRC (Bastos et al., 2024). As comparable long-term projections for all EU countries are not available or only available to a limited extent, trend-based projections were derived for this thesis. These are based on the average annual changes over the most recent six reporting years and should highlight the diversity of trajectories within the European Union.

Figure 10 presents both historic and projected data for grid renewable shares and carbon intensity in Germany, Sweden and Italy, as well as the EU27 average. Sweden represents a country already well advanced in the energy transition, with a renewable share close to 100 percent and grid carbon intensity near zero. Germany has committed to an 80 percent renewable share by 2030 and aims for full climate neutrality by 2045, five years earlier than the EU target. Based on current expansion rates in wind and solar installations, Germany is on track to meet its 2030 target. Italy, in contrast, shows a slower pace of decarbonization, with current trends indicating potential challenges in reaching EU targets without additional policy interventions.

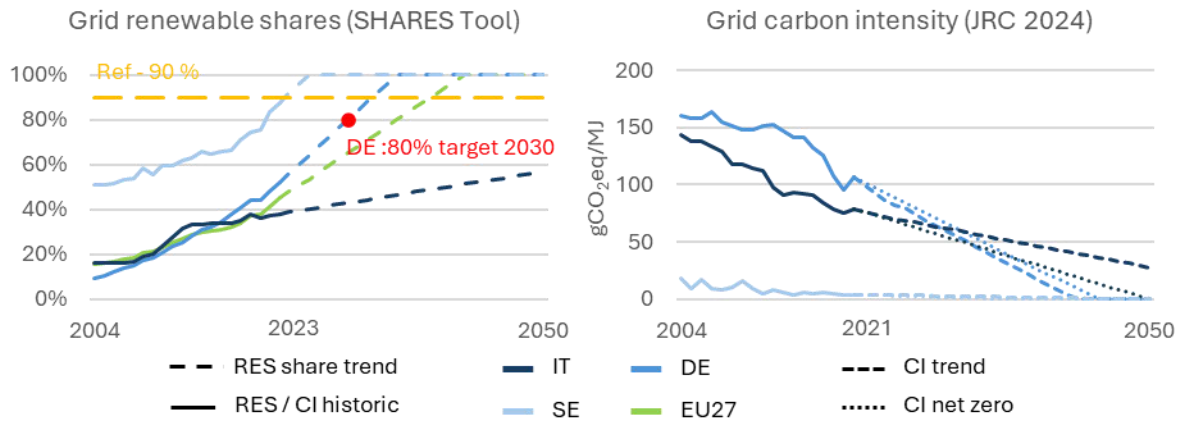


Figure 10: (both) Exemplary RES and CI data for Italy, Germany, Sweden & EU27 (left) historic RES share until 2023* and derived trend projections based on the previous 6 years. (right) Historic carbon intensities until 2021**, trend projections based on the previous 6 years and required decarbonization pathways to reach EU net zero target by 2050 (DE by 2045); *Data from SHARES Tool 2023 (Eurostat Database, 2025); ** Data from JRC data catalogue (Bastos et al., 2024)

In this thesis, projections for Germany are used as the reference case for implementing grid carbon intensity in the simulation model. This ensures consistency with the electricity pricing assumptions discussed in the previous section. Thus, grid carbon intensity should be considered as a scenario-dependent input, applied according to the latest available trend data from official sources.

It is important to highlight that, as discussed in Chapter 3.1.3, surpassing a 90 % renewable share in the national grid grants RFNBO producers significant regulatory easements with regards to fully renewable electricity sourcing. However, to maintain a conservative and robust basis for analysis, these regulatory relaxations should not be considered in the model. Even if the grid crosses the 90 % threshold during the plant's operational lifetime, this thesis assumes a sub-90 % RES share to evaluate P2A system performance under stricter compliance conditions.

4.2 Power-to-Ammonia Process

The following section will discuss key technical and economic characteristics of the P2A processing steps. Relevant constraints and requirements to be considered in the model of a P2A process will be derived.

4.2.1 BESS

As described in Chapter 2.2.3, this thesis considers lithium-ion (Li-ion) battery technology for the BESS. Over recent years, the investment costs for Li-ion BESS have experienced a significant decline, driven by technological advancements and scaling effects (Orangi et al., 2024).

Capital Expenditure (CapEx): In the literature, BESS investment costs are commonly reported as capacity-specific capital costs (i.e., EUR/kWh), typically without explicit differentiation between power and energy ratings or discharge duration (Campion et al., 2023; Sens et al., 2022;

Wang et al., 2023). These values range between 300 and 360 EUR/kWh. A more differentiated estimate is provided by the 2024 Annual Technology Baseline (ATB) of the National Renewable Energy Laboratory (NREL), which distinguishes between power-specific and capacity-specific investment costs. For the 2025 moderate scenario, adjusted from 2022 values and converted to EUR using historical exchange rates, the capital costs amount to 274 EUR/kW and 273 EUR/kWh, respectively (NREL, 2024).

Operational Expenditure (OpEx): Annual maintenance costs for Li-ion BESS typically range between 2% and 3% of the initial CapEx. In this work, a value of 2% is assumed (Sens et al., 2022).

Efficiency: Reported efficiencies of Li-ion BESS systems in literature vary between 85% and 91%, depending on the reporting method – either as overall roundtrip efficiency or as separate charging and discharging efficiencies (Campion et al., 2023; Wang et al., 2023). In this thesis, a charging efficiency of 96% and a discharging efficiency of 95% are assumed, resulting in a roundtrip efficiency of approximately 91%, aligning with typical values reported by Campion et al. (2023).

Lifetime, degradation, and replacement: BESS degradation in modelling studies is generally implemented using either calendar or cycling ageing mechanisms (Vykhodtsev et al., 2022). For simplification purposes, this thesis considers cycling ageing as the primary degradation mechanism. Capacity degradation depends on the application profile (e.g., frequency containment reserve, day-ahead, intraday markets), with average annual degradation typically falling between 1% and 2%. A representative value of 1.55% is applied in this work (Gräf et al., 2022).

To mitigate degradation, a maximum depth of discharge (DoD) corresponding to 80% of nominal capacity is assumed. End of operational lifetime is reached when the battery degrades to 80% of its original capacity, meaning 80% state of health (SoH). Based on the degradation assumptions, this threshold would be reached after approximately 12.9 years, which is rounded to 13 years. At that point, a full replacement is modelled at 50% of the original investment cost, reflecting anticipated future cost reductions in Li-ion battery technology (Benson, 2023).

4.2.2 Electrolyzer

For the simulation model developed in this thesis, AEL is selected as the electrolyzer technology. The choice is based on AEL's high technological maturity, cost-effectiveness and its proven large-scale deployment in industrial hydrogen production processes (Campion et al., 2023).

CapEx: In literature reported specific investment costs for AEL systems range from 1000 EUR/kW to 1,200 EUR/kW (El-Shafie, 2023). To maintain a conservative cost assumption, this thesis applies the upper bound of 1,200 EUR/kW.

OpEx: Annual maintenance costs are typically assumed to lie between 2% and 3% of the initial CapEx (Campion et al., 2023; Yu et al., 2024). A value of 2% CapEx per year is assumed in this work.

Dynamic Response and Operational Range: Compared to PEMEL, AEL has a significantly lower ramp-rate. AEL systems are reported with ramping capabilities around 0.3% of nominal power per second, whereas PEMEL systems can achieve ramp-rates between 10% and 40% per second (Martinez Lopez et al., 2023). However, given the hourly temporal resolution of the simulation in this thesis, such ramp-rate limitations are not restrictive. Consequently, ramp-rate dynamics for the AEL are not explicitly modelled.

Regarding partial load capabilities, AEL typically exhibits a minimum operational load between 20% and 30% of its rated capacity (El-Shafie, 2023; Martinez Lopez et al., 2023). However, these values largely stem from analyses of single-system electrolyzers. In the context of industrial-scale deployment involving multiple modular units aggregated to potentially several hundred megawatts, lower minimum load thresholds are feasible. Therefore, a reduced minimum load of 5% of rated power is assumed in this thesis, following the approach of Yu et al. (2024).

Efficiency and specific electricity consumption: The specific electricity consumption of AEL systems typically ranges from 47 to 66 kWh/kg_{H₂}, which corresponds to efficiencies between 50% and 68% when referred to the LHV of hydrogen (Martinez Lopez et al., 2023). Some studies model load-dependent efficiency curves to reflect operational non-linearities more accurately. For instance, Kopp (2018) provides an empirical efficiency-load curve derived from an operational plant, while Ikäheimo et al. (2018) approximate efficiency profiles using a step function. Nevertheless, to reduce model complexity and enhance computational efficiency, a simplified approach is adopted here: a constant specific electricity consumption is assumed across the entire load range. This approach aligns with simplifications used in other techno-economic studies (Campion et al., 2023; Yu et al., 2024). The specific electricity demand selected in this thesis will be 55.5 kWh/kg_{H₂} equivalent to 60% efficiency taken from Yu et al. (2024).

In terms of operating conditions, the AEL units are assumed to operate at a pressure of 30 bar and an outlet temperature of 60 °C.

Degradation and replacement: Stack lifetime for AEL systems is reported to range from 60,000 to 90,000 operating hours, depending on acceptable efficiency degradation (El-Shafie, 2023). Due to intermittent operation of the AEL using fluctuating renewables, faster degradation is to be expected (Martinez Lopez et al., 2023). Consequently, the stack lifetime is set to 70,000 hours, resulting in a replacement cycle of approximately 8 years. Stack degradation is modelled at an average rate of 2% per year, which corresponds to an increase in cell voltage of 4 µV/h for a 1.8 V AEL system (Lee et al., 2023). Stack replacements are assumed to occur at 50% of the initial CapEx, reflecting anticipated technological learning and cost reductions (Campion et al., 2023).

4.2.3 Compressor

The H₂ storage compressor capacity is scaled to the maximum output of the electrolyzer, ensuring that hydrogen production under full-load operation can be fully compressed and stored.

CapEx and OpEx: Reported specific investment costs for hydrogen compressors range from 1,780 to 2,500 EUR/kg_{H₂}/h, depending on pressure limits between 100 and 250 bar (Sens et

al., 2022; Terlouw et al., 2022). In this thesis, a value of 2,000 EUR/kg_{H₂}/h is assumed. Maintenance costs are reported between 4–5 % of CapEx per year; here, 4.5 % is used.

Specific electricity demand: The previously cited studies report a compressor efficiency of 79 %. The required energy to compress hydrogen is calculated using Equation (6), based on the plant parameters. As described in Chapter 2.2.5, the specific work depends on the hydrogen storage pressure level, which increases with SOC. Higher storage levels require more energy input to inject additional hydrogen. Accurately modelling this non-linear relationship would require iterative numerical calculation. Within this thesis, an average electricity demand has been assumed. Using a mean gas factor of 1.05, a polytropic coefficient of 1.3, a compressor inlet pressure of 30 bar and temperature of 60 °C, the universal gas constant (8.3145 J/(mol·K)), hydrogen molar mass (2.0159 kg/mol), the given efficiency of 79 %, and a storage pressure of 200 bar, the average electricity demand for compression is calculated to be 0.62 kWh/kg_{H₂}.

Degradation and losses: Degradation and H₂ losses during compression are neglected, as was also done by Yu et al. (2024).

4.2.4 Pressurized H₂ Storage

After compression, excess hydrogen is stored in a pressurized hydrogen storage system. Compressed hydrogen storage is selected for this thesis, as it is currently the most cost-effective and commercially established solution (Mulky et al., 2024). The often-cited drawback of low volumetric energy density, especially when compared to liquid hydrogen, can be neglected in this case. For stationary, industrial applications, land use is typically not a limiting factor, whereas cost and energy efficiency are far more relevant.

CapEx and OpEx: Sens et al. (2022) report a specific investment cost of 467 EUR/kg_{H₂} for a 200 bar pressurized type II steel tank system. Champion et al. (2023) apply 461 EUR/kg_{H₂} for a 100 bar storage concept based on buried steel piping. In this thesis 460 EUR/kg_{H₂} for a 200 bar system is used. Annual maintenance costs are typically reported between 1 % and 2 % of CapEx (Sens et al., 2022; Terlouw et al., 2022). A midpoint of 1.5 % is assumed for the model.

Lifetime and replacement: The operational lifetime of pressurized hydrogen storage systems is reported to range between 20 and 30 years (Sens et al., 2022; Terlouw et al., 2022). Therefore, no system replacement is assumed within the modelled economic lifetime of the project.

4.2.5 Haber-Bosch Process with ASU

The Haber-Bosch synthesis loop and the ASU are considered as a combined processing step, as done in many comparable techno-economic models (Narciso et al., 2025).

CapEx and OpEx: Specific investment costs for Haber-Bosch and ASU systems are expected to be scale-dependent, as is typical for industrial chemical installations (Cheali et al., 2015). However, this assumption cannot be clearly confirmed based on the reviewed literature, due to inconsistencies in reported CapEx (e.g. currency units, lack of time-indexing, unknown plant sizes and differing system characteristics). Reported estimates range from 3,800 to 4,900 EUR/(kg_{NH₃}/h) for plant capacities between 35 and 430 kta (Armijo and Philibert, 2020; Bose et al., 2022; Champion et al., 2023; Ikäheimo et al., 2018; Wang et al., 2023). In this thesis,

the cost estimate by Campion et al. (2023) is applied: 4,092 EUR/(kg_{NH₃}/h) for a 64 t_{NH₃}/h plant including the ASU.

Annual maintenance costs for both units are assumed at 2 % of CapEx, in line with existing literature (Armijo and Philibert, 2020; Ikäheimo et al., 2018).

Electricity and hydrogen demand: Electricity consumption includes the compressor load of the synthesis loop and the power demand of the ASU. For cryogenic air separation, specific demands between 0.25 and 0.84 kWh/kg_{N₂(l)} are reported (Wu et al., 2020), which translates to approximately 0.20–0.69 kWh/kg_{NH₃}, based on stoichiometric N₂ consumption². Klyapovskiy et al. report a combined demand of 0.90 MWh/t_{NH₃}, of which 0.64 MWh/t_{NH₃} is attributed to synthesis loop compression and 0.26 MWh/t_{NH₃} to the ASU (Klyapovskiy et al., 2021). Armijo and Philibert (2020) assume a total specific demand of 0.64 MWh/t_{NH₃} without further breakdown, which equals approximately 12.4 % of the chemical energy output based on ammonia's LHV. This value will be used in this thesis.

The stoichiometric hydrogen demand for ammonia production is 0.176 kg_{H₂}/kg_{NH₃}³. Due to purging of inert gases in the recycle loop, this ideal value is not fully achievable. Effective conversion rates reported in the literature range from 4.89 to 5.29 kg_{NH₃}/kg_{H₂}, which corresponds to hydrogen purge losses of 6.5 to 12.5 % (Campion et al., 2023; Osman et al., 2020). A 10 % purge loss is assumed, leading to a specific H₂ demand of 0.196 kg_{H₂}/kg_{NH₃}.

Operational flexibility and load behaviour: The dynamic operability of the Haber-Bosch process remains a central challenge. According to a white paper by Haldor Topsoe, load flexibility of up to 90 % and even 100 % with electricity and H₂ storage is technically possible (Alfa Laval et al., 2020). However, such values are questioned by Wang et al. (2023), based on the steady-state design of conventional SMR-based systems – a concern supported by Yu et al. (2024). A P2A process review suggests a more conservative flexibility range between 20 % and 80 %, with 50 % considered a reasonable compromise for modelling purposes (Narciso et al., 2025; Wang et al., 2023).

Modelling the synthesis as a fixed continuous load results in high storage capacity requirements and increased curtailment of renewable electricity (Narciso et al., 2025; Yu et al., 2024). Conversely, modelling it as a fully flexible unit without operational limits raises concerns around thermal and pressure stability (Sánchez and Martín, 2018). Wang et al. (2023) and Yu et al. (2024) both implement ramp-rate restrictions of 20 % per hour within their MILP-based optimization frameworks. While reasonable in those contexts, such a constraint would require predictive capabilities to implement within a rule-based dispatch logic, which goes beyond the reasonable scope of the simulation and is therefore acknowledged for completeness but not included in this thesis.

² Nitrogen mass fraction in ammonia: $\omega_{N_2} = \frac{M_{N_2}}{M_{NH_3}} = \frac{14}{17} = 0,823 \frac{kg_{N_2}}{kg_{NH_3}}$

³ Hydrogen mass fraction in ammonia: $\omega_{H_2} = \frac{M_{H_2}}{M_{NH_3}} = \frac{3}{17} = 0,176 \frac{kg_{H_2}}{kg_{NH_3}}$

Shutdown and restart behaviour: In the event of full shutdown, the Haber-Bosch synthesis requires a restart delay of several days. Armijo and Philibert (2020) assume a cold restart delay of 48 hours, which is adopted here.

Degradation and lifetime: No explicit degradation effects are modelled. Catalyst degradation, the primary ageing mechanism, is assumed to be reflected in the general maintenance cost. The operational lifetime of the synthesis unit is reported between 20 and 30 years (Armijo and Philibert, 2020; Ikäheimo et al., 2018), which falls within the assumed project lifetime and thus requires no replacement.

4.3 General Assumptions

This section covers general economic assumptions that are not assigned to a specific unit operation within the RFNBO ammonia system, but are essential for a consistent techno-economic evaluation. These include the assumed project lifetime, inflation rate and financing structure. While these parameters do not affect the technical feasibility, they have a significant influence on the levelized cost of ammonia (LCOA) and are therefore integrated into the economic layer of the simulation framework.

Project lifetime: The project lifetime is defined as the sum of the construction and commissioning phase and the subsequent operational period. In this thesis, the construction phase is assumed to take place over three years, followed by a 20-year operational period, resulting in a total project duration of 23 years.

Inflation: This thesis assumes an annual inflation rate of 2% over the full project lifetime. This value corresponds to the long-term inflation target of the European Central Bank (ECB, 2024). Inflation is considered when calculating P2A maintenance cost, as they are the only modelled variable OpEx, that would not be covered by long term fixed price agreements (i.e. PPA).

Financing assumptions: The investment in the RFNBO ammonia plant is assumed to be realized through a typical project finance structure, combining equity and debt capital (Yescombe, 2014, chap. 12). WACC is calculated according to Equation (9) using the parameters listed in Table 5. These values result in a nominal WACC of 7.7%, equivalent to discount rates assumed in comparable studies (Campion et al., 2023; Yu et al., 2024). All capital expenditures, operational costs and revenues are discounted accordingly.

Initial CapEx will be distributed throughout the construction phase for year₁ / year₂ / year₃ with 30%CapEx / 50%CapEx / 20%CapEx.

4.4 Summary of Input Assumptions and Derived Simulation Constraints

Based on the techno-economic analysis of P2A processes found in the literature, the assumptions and simulation requirements relevant to this thesis have been derived. These are summarized in Table 5 and Table 6 below.

Table 5: Overview of derived input assumptions

Component	Parameter	Unit	Value	Reference
RES	El. price – Wind high FLH	EUR/MWh	65	see Table 4
	El. price – Wind low FLH	EUR/MWh	90	see Table 4
	El. price – PV high FLH	EUR/MWh	45	see Table 4
	El. price – PV low FLH	EUR/MWh	50	see Table 4
	PPA contract duration	a	20	authors assumption
Grid	Spot el. sales price	EUR/MWh	0	authors assumption
	Spot el. purchasing price	EUR/MWh	150	authors assumption
BESS	Spec. CapEx (power)	EUR/kW	274	(NREL, 2024)
	Spec. CapEx (capacity)	EUR/kWh	273	(NREL, 2024)
	Spec CapEx replacement	EUR/kWh	$0.5 \cdot \text{CapEx}_{\text{kWh}}$	(Benson, 2023)
	OpEx	$\%_{\text{CapEx/a}}$	2.5	(Sens et al., 2022)
	Charge efficiency	%	96	(Campion et al., 2023; Wang et al., 2023)
	Discharge efficiency	%	95	(Campion et al., 2023; Wang et al., 2023)
	Capacity degradation	$\%_{\text{kWh/a}}$	1.55	(Gräf et al., 2022)
	Lifetime	a	13	(Benson, 2023)
AEL	Spec. CapEx	EUR/kW	1,200	(El-Shafie, 2023)
	Spec. CapEx replacement	EUR/kW	$0.5 \cdot \text{CapEx}_{\text{kW}}$	(Campion et al., 2023)
	OpEx	$\%_{\text{CapEx/a}}$	2	(Campion et al., 2023; Yu et al., 2024)
	Spec. el energy demand	kWh/kg _{H₂}	55.5	(Yu et al., 2024)
	Minimum load	$\%_{\text{P}_{\text{nom}}}$	5	(Yu et al., 2024)
	Pressure	bar	30	Own assumption
	Temperature	°C	60	Own assumption
	Degradation	$\%_{\text{kW/a}}$	2	(Lee et al., 2023)
Compressor	Stack lifetime	a	8	(Lee et al., 2023)
	Spec. CapEx	EUR/(kg _{H₂} /h)	2,000	(Sens et al., 2022; Terlouw et al., 2022)
	OpEx	$\%_{\text{CapEx/a}}$	4.5	(Sens et al., 2022; Terlouw et al., 2022)
	Efficiency	$q_{\text{ideal}}/q_{\text{real}}$	0.79	(Sens et al., 2022)
H ₂ storage	Avg compressor work (30 to 200 bar)	kWh/kg _{H₂}	0.62	authors assumption
	Spec. CapEx	EUR/kg _{H₂}	460	(Campion et al., 2023; Sens et al., 2022)
	OpEx	$\%_{\text{CapEx/a}}$	1.5	(Sens et al., 2022; Terlouw et al., 2022)
	Max pressure	bar	200	(Sens et al., 2022)
Haber-Bosch (incl. ASU)	Lifetime	a	25	(Sens et al., 2022; Terlouw et al., 2022)
	Spec. CapEx	EUR/(kg _{NH₃} /h)	4,092	(Campion et al., 2023)
Haber-Bosch (incl. ASU)	OpEx	$\%_{\text{CapEx/a}}$	2	(Armijo and Philibert, 2020; Ikäheimo et al., 2018)

Component	Parameter	Unit	Value	Reference
	Spec. el energy demand	kWh/kg _{NH₃}	0.64	(Armijo and Philibert, 2020)
	Spec. H ₂ demand	kg _{H₂} /kg _{NH₃}	0.196	(Campion et al., 2023; Osman et al., 2020)
	Minimum load	% _{P_{nom}}	50	authors assumption
	Cold shutdown demand	MW	0	(Armijo and Philibert, 2020)
	Restart delay	h	48	(Armijo and Philibert, 2020)
	Lifetime	a	25	(Armijo and Philibert, 2020; Ikäheimo et al., 2018)
General	Project lifetime (Con + Op)	a	3 + 20	authors assumption
	Inflation	%/a	2	(ECB, 2024)
	Equity share	%	40	authors assumption
	Debt share	%	60	authors assumption
	Cost of equity	%	13	authors assumption
	Cost of debt	%	6	authors assumption
	Corporate tax rate	%	30	authors assumption

Table 6: Overview of derived technical and economic requirements to be considered in the simulation model

Component	Techno-economic requirement	Simulation constraint / demand
RES	Hourly profiles	Enable dynamic RES asset configuration
Grid	Carbon intensity grid	Annual updating of grid emissions intensity according to projections
Haber-Bosch synthesis	Minimum load, cold restart delay	Minimum operational load enforced; in case of shutdown restarts delayed
AEL	Minimum load operability, constant efficiency, annual stack degradation	Minimum load threshold at, fixed specific energy consumption; annual degradation implemented
BESS	Efficiency losses, depth of discharge, calendar degradation	Charging/discharging efficiencies enforced; usable BESS capacity range, capacity modelled annually
Component lifetimes	Limited operational lifetimes for AEL stacks and BESS units	Replacement modelled with required CapEx at defined intervals
Mass-energy consistency	Thermodynamic and stoichiometric balance of all mass and energy flows	Mass and energy conservation enforced throughout all modelled units
Cashflow structure	Annualized economic representation of cost flows	Costs aggregated monthly; inflation applied; values discounted using WACC
LCOA calculation	Requires aggregated costs and production over time	Time-resolved cost and production values aggregated for LCOA using nominal cashflow accounting

5 Simulation Model Design

To model a P2A process that exclusively yields RFNBO-compliant ammonia, the regulatory and techno-economic requirements derived in chapters 3 and 4 are translated into a computational framework using Python. This chapter outlines the structure of the simulation model, its mathematical formulation, the dispatch strategy applied and the evaluation of KPIs. The model development and validation process are also discussed.

5.1 Model Structure and Mathematical Description

5.1.1 Process Flow

The model structure reflects the sequential flow of energy and materials through the P2A system as shown in the P2A process flowchart in Figure 11. The connecting lines either indicate the flow of electrical energy and its respective source, or the mass flow of relevant synthesis gases and final RFNBO ammonia product.

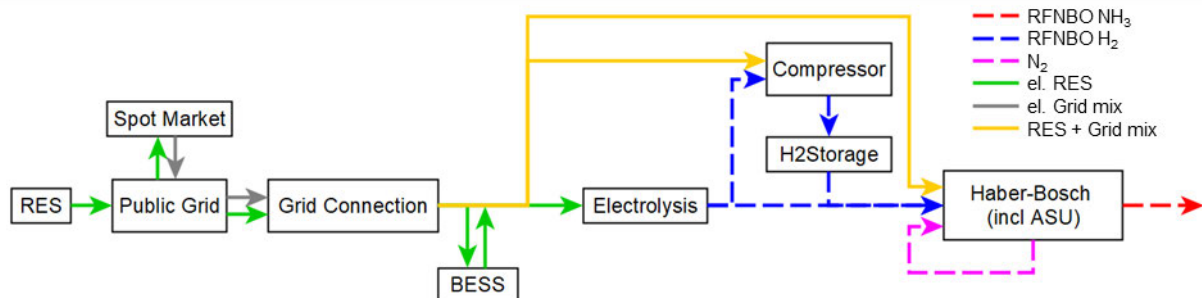


Figure 11: Basic flowchart of the modelled P2A process. Dashed lines indicate a mass flow (H_2 , N_2 , NH_3) and straight lines the electric energy flow (RES, grid mix, combined).

Green lines show the flow of fully renewable electricity transmission via the public grid. Spot market interactions consist of reselling unused surplus electricity from the PPA and buying additional grid mix electricity (grey arrows). Once the combined electrical energy flow reaches the plant site through the grid connection, it is distributed to the main consumers included in the model. While electrolysis and BESS are only supplied with fully renewable electricity, the H_2 -storage compressor and the Haber-Bosch processing step, including the air separation unit, may consume a mix of fully renewable electricity and grid mix (yellow arrows).

Hydrogen fed to the Haber-Bosch process can either be supplied directly from the electrolyzer or from the H_2 storage tank. It is important to note, that the carbon intensity of supplied H_2 from electrolyzer and storage may vary due to additional emissions, allocated to H_2 transferred to storage, from grid mix consumption in the compressor. Both H_2 streams will be RFNBO compliant though ($< 28.2 \text{ gCO}_2\text{eq/MJ}$). N_2 production (pink arrow) in the ASU is not individually

considered in the model, but included in the Haber-Bosch processing step, as is done in many comparable model implementations found in the literature.

5.1.2 P2A Process Unit Models

The following sections present the core mathematical relationships used to describe the behaviour of each system unit.

Renewable Electricity Source

The available renewable electricity $E_{\text{RES},t}$ at each timestep t is calculated as the sum of the nominal rated power $P_{\text{RES,nom},i}$ of all renewable assets multiplied by their respective capacity factors $CF_{i,t}$:

$$E_{\text{RES},t} = \sum_{i \in \text{RES}} P_{\text{RES,nom},i} \cdot CF_{i,t} \cdot \Delta t \quad (12)$$

Battery (BESS)

The BESS state of charge $SOC_{\text{BESS},t}$ at each timestep is calculated by dividing the el. energy stored in the BESS $E_{\text{BESS},t}$ by the maximum capacity of the BESS $E_{\text{BESS,cap},t}$. Since the BESS capacity is subjected to degradation effects, $E_{\text{BESS,cap},t}$ decreases over time as calculated using Equation (14):

$$SOC_{\text{BESS},t} = \frac{E_{\text{BESS},t}}{E_{\text{BESS,cap},t}} \quad (13)$$

$$E_{\text{BESS,cap},t} = E_{\text{BESS,cap},0} \cdot (1 - \delta_{\text{cap}} \cdot y_t) \quad \text{with} \quad y_t = \left\lfloor \frac{t}{n_{\text{h,month}}} \right\rfloor \cdot \frac{1}{12} \quad (14)$$

When charging and discharging el. energy to and from the BESS, internal losses $E_{\text{BESS,loss},t}$ are considered through charging η_{cha} and discharging η_{dis} efficiencies. $E_{\text{BESS,in},t}$ and $E_{\text{BESS,out},t}$ represent the energy moved into and taken out of the BESS system, while $E_{\text{BESS,char},t}$ and $E_{\text{BESS,dis},t}$ indicate the change in actual energy stored $E_{\text{BESS},t}$:

$$E_{\text{BESS},t} = E_{\text{BESS},t-1} + E_{\text{BESS,char},t} - E_{\text{BESS,dis},t} = E_{\text{BESS},t-1} + E_{\text{BESS,in},t} \cdot \eta_{\text{cha}} - \frac{E_{\text{BESS,out},t}}{\eta_{\text{dis}}} \quad (15)$$

$$E_{\text{BESS,loss},t} = E_{\text{BESS,in},t} - E_{\text{BESS,char},t} + E_{\text{BESS,dis},t} - E_{\text{BESS,out},t} \quad (16)$$

Technical power and capacity constraints are implemented for charging and discharging:

$$E_{\text{BESS,in},t} \leq P_{\text{BESS,nom}} \cdot \Delta t, \quad E_{\text{BESS,out},t} \leq P_{\text{BESS,nom}} \cdot \Delta t, \quad E_{\text{BESS},t} \leq E_{\text{BESS,cap},t} \quad (17)$$

BESS is implemented with a conditional minimum storage level requirement. This will further be explained in chapter 5.2. In short: when RE from BESS is needed to ensure operation of

the Haber-Bosch, $SOC_{BESS,min}$ may be dismissed. If Haber-Bosch operation above minimum load is possible, recharging of BESS to $SOC_{BESS,min}$, has priority.

$$SOC_{BESS,t} \geq SOC_{BESS,min} \quad (18)$$

Alkaline Electrolysis (El)

Hydrogen production in the AEL is described by Equation (19), where the el. energy $E_{El,t}$ supplied to the AEL is divided by the specific el. demand $SEC_{El,t}$ to calculate the amount of hydrogen $m_{H_2,El,t}$ produced for each timestep. Since the AEL may only be consume fully renewable el. energy, the carbon intensity of H_2 from AEL $CI_{H_2,El,t}$ is always assumed to be 0.

$$m_{H_2,El,t} = \frac{E_{El,t}}{SEC_{El,t}} = m_{H_2,El \rightarrow Syn,t} + m_{H_2,El \rightarrow Co,t} \quad \text{with} \quad E_{El,t} = E_{El,RES,t} + E_{El,BESS,t} \quad (19)$$

Stack degradation in the AEL is considered by a monthly increase in $SEC_{El,t}$ relative to the annual degradation factor δ_{El} .

$$SEC_{El,t} = SEC_{El,0} \cdot (1 + \delta_{El} \cdot y_t) \quad \text{with} \quad y_t = \left\lfloor \frac{t}{n_{h,month}} \right\rfloor \cdot \frac{1}{12} \quad (20)$$

The AEL's load is only allowed within the operational window restricted by minimum turndown rate $\lambda_{El,min}$ and nominal rated power $P_{El,nom}$. No standby consumption is assumed.

$$E_{El,t} \in \{0\} \cup [P_{El,nom} \cdot \lambda_{El,min} \cdot \Delta t, \quad P_{El,nom} \cdot \Delta t] \quad (21)$$

Compressor (Co)

The total energy consumed by the compressor $E_{Co,t}$ is calculated by multiplying the H_2 $m_{H_2,El \rightarrow Co,t}$ supplied from the AEL by the specific electricity consumption of the compressor SEC_{Co} . There are no H_2 losses and degradation effects considered:

$$E_{Co,t} = SEC_{Co} \cdot m_{H_2,El \rightarrow Co,t} = E_{Co,RES,t} + E_{Co,grid,t} + E_{Co,BESS,t} \quad (22)$$

$$m_{H_2,El \rightarrow Co,t} = m_{H_2,Co \rightarrow St,t} \quad (23)$$

The compressor can consume grid mix electricity that introduces GHG emissions with CI_{grid} . These emissions are allocated to the H_2 leaving the compressor, resulting in a carbon intensity of hydrogen fed to storage, that may not be zero. $CI_{H_2,Co \rightarrow St,t}$ is calculated using Equation (24). A maximum carbon intensity for H_2 transferred to storage $CI_{H_2,Co \rightarrow St,max}$ can be selected and is implemented as an operational constraint on the compressor.

$$CI_{H_2,Co \rightarrow St,t} = \frac{E_{Co,grid,t} \cdot CI_{grid}}{m_{H_2,El \rightarrow Co,t} \cdot LHV_{H_2}} \leq CI_{H_2,Co \rightarrow St,max} \quad (24)$$

H₂ Storage (St)

To ensure traceability of GHG emissions allocated to H₂ transferred to St, a batch system is implemented in St. The set $\mathcal{B}_t$ consists of the ordered sum of batches β_i at time t . A batch is defined by the time it has been stored t_i , the amount of H₂ stored m_i during the distinct hourly window and the associated emission intensity CI_i .

$$\mathcal{B}_t = \{ \beta_i \mid \sum_i m_i = m_{H_2,St,t} \} \quad \text{with} \quad \beta_i = (t_i, CI_i, m_i) \quad (25)$$

The state of charge of St $SOC_{St,t}$ at any given time t can be described by the total amount of H₂ stored $m_{H_2,St,t}$ and its average carbon emission intensity $CI_{H_2,St,t}$:

$$SOC_{St,t} = \frac{m_{H_2,St,t}}{m_{H_2,St,cap}}, \quad m_{H_2,St,t} = \sum_{i \in \mathcal{B}_t} m_i, \quad CI_{H_2,St,t} = \frac{\sum_{i \in \mathcal{B}_t} m_i \cdot CI_i}{\sum_{i \in \mathcal{B}_t} m_i} \quad (26)$$

The H₂ balance for each timestep t is defined by the total H₂ stored in St at the last timestep $m_{H_2,St,t-1}$ plus total H₂ received from Co $m_{H_2,Co \rightarrow St,t}$ and minus total H₂ transferred to the Haber-Bosch process $m_{H_2,St \rightarrow Syn,t}$:

$$m_{H_2,St,t} = m_{H_2,St,t-1} + m_{H_2,Co \rightarrow St,t} - m_{H_2,St \rightarrow Syn,t} \quad \text{with} \quad m_{H_2,St,t-1} = \sum_{i \in \mathcal{B}_{t-1}} m_i \quad (27)$$

When storing H₂, a new batch is amended to the batch collection.

$$\mathcal{B}_t = \mathcal{B}_{t-1} \cup \{ \beta_{\text{new}} \} \quad \text{with} \quad \beta_{\text{new}} = (t, CI_{H_2,Co \rightarrow St,t}, m_{H_2,Co \rightarrow St,t}) \quad (28)$$

When removing H₂, the “oldest” batches are removed first (FIFO). Depending on the amount of H₂, a batch might only be partially discharged, leaving the rest in storage β_k^{res} . Amount of discharged H₂ and its associated carbon intensity are based on the subset of batches D_t removed from St:

$$\mathcal{B}_t = \mathcal{B}_{t-1} \setminus D_t \cup \{ \beta_k^{\text{res}} \} \quad \text{with} \quad D_t \subset \mathcal{B}_{t-1} \quad (29)$$

$$m_{H_2,St \rightarrow Syn,t} = \sum_{i \in D_t} m_i, \quad CI_{H_2,St \rightarrow Syn,t} = \frac{\sum_{i \in D_t} m_i \cdot CI_i}{\sum_{i \in D_t} m_i} \quad (30)$$

As with BESS, St is also implemented with a conditional minimum storage requirement.

$$SOC_{St,t} \geq SOC_{St,\min} \quad (31)$$

Haber-Bosch incl. ASU (Syn)

Equation (32) shows how NH₃ output $m_{NH_3,t}$ can be calculated from both H₂ input $m_{H_2,Syn,t}$ and el. energy input $E_{Syn,t}$, using the specific hydrogen demand SHC_{Syn} and specific electricity demand SEC_{Syn} , respectively:

$$m_{\text{NH}_3,t} = \frac{m_{\text{H}_2,\text{Syn},t}}{\text{SHC}_{\text{Syn}}} = \frac{E_{\text{Syn},t}}{\text{SEC}_{\text{Syn}}} \quad (32)$$

$$m_{\text{H}_2,\text{Syn},t} = m_{\text{H}_2,\text{El} \rightarrow \text{Syn},t} + m_{\text{H}_2,\text{St} \rightarrow \text{Syn},t}, \quad E_{\text{Syn},t} = E_{\text{Syn},\text{RES},t} + E_{\text{Syn},\text{grid},t} + E_{\text{Syn},\text{BESS},t} \quad (33)$$

The carbon intensity of produced NH_3 is calculated from emissions from grid electricity and H_2 supplied from H_2 storage used in the Haber-Bosch synthesis:

$$CI_{\text{NH}_3,t} = \frac{E_{\text{Syn},\text{grid},t} \cdot CI_{\text{grid}} + m_{\text{H}_2,\text{St} \rightarrow \text{Syn},t} \cdot CI_{\text{H}_2,\text{St} \rightarrow \text{Syn},t} \cdot \text{LHV}_{\text{H}_2}}{m_{\text{NH}_3,t} \cdot \text{LHV}_{\text{NH}_3}} \leq CI_{\text{Budget}} \quad (34)$$

The model ensures, that the carbon intensity of NH_3 never surpasses the GHG emission threshold of 28.2 gCO₂eq/MJ in order to comply with the 70% GHG saving the requirements and to qualify as RFNBO (Equation (10) and (11)). Since the model only accounts for emissions associated to the ammonia production process (EXW), other emissions stemming from transport, further processing and final use are combined into a flat CI-contribution CI_{others} . The difference between CI_{RFNBO} and CI_{others} , gives the effective maximum carbon intensity, that $CI_{\text{NH}_3,t}$ cannot exceed:

$$CI_{\text{Budget}} = CI_{\text{RFNBO}} - CI_{\text{others}} \geq CI_{\text{NH}_3,t} \quad (35)$$

Like the operational window of the AEL, the operation of the Haber-Bosch unit is also limited by its nominal operating power and the minimum threshold. In contrast to the AEL, a standby consumption equal to the el. energy demand at minimum load is assumed. Once shut down, the Haber-Bosch unit remains shutdown until the restart timer has run out.

$$\text{If } m_{\text{NH}_3,t}, m_{\text{H}_2,\text{Syn},t} > 0 \Rightarrow E_{\text{Syn},\text{in},t} \in [P_{\text{Syn},\text{nom}} \cdot \lambda_{\text{Syn},\text{min}} \cdot \Delta t, P_{\text{Syn},\text{nom}} \cdot \Delta t] \quad (36)$$

$$\text{If } m_{\text{NH}_3,t}, m_{\text{H}_2,\text{Syn},t} = 0 \Rightarrow E_{\text{Syn},\text{in},t} = E_{\text{Syn},\text{standby}} = P_{\text{Syn},\text{nom}} \cdot \lambda_{\text{Syn},\text{min}} \cdot \Delta t \quad (37)$$

5.1.3 System Balance equations

In addition to the unit-specific models, the simulation model enforces system-wide balance equations at every timestep. These balances ensure mass, energy and GHG accounting consistency across all modelled process units. By maintaining strict balancing, the model guarantees that the simulated P2A process remains physically realistic and regulatorily traceable.

El. Energy Balance:

The model ensures that at every timestep t , the total el. energy supplied to the systems matches the total consumption.

$$E_{\text{supply},t} = E_{\text{consumption},t} \quad (38)$$

$$E_{\text{RES},t} + E_{\text{Grid},t} + E_{\text{BESS},\text{out},t} = E_{\text{El},t} + E_{\text{Syn},t} + E_{\text{Comp},t} + E_{\text{BESS},\text{in},t} + E_{\text{surplus},t}$$

Mass Balance

The model tracks all mass flows of hydrogen produced, stored, consumed and compressed. The mass balance ensures that the hydrogen supplied equals the hydrogen consumed in each timestep:

$$m_{H_2,supply,t} = m_{H_2,consumption,t} \quad (39)$$

$$m_{H_2,El \rightarrow Syn,t} + m_{H_2,El \rightarrow Co,t} + m_{H_2,Co \rightarrow St,t} + m_{H_2,St \rightarrow Syn,t} = m_{H_2,Syn,t} + m_{H_2,St,in,t} + m_{H_2,Co,in,t}$$

GHG Emission Balance

The GHG emission balance ensures, that emissions are tracked for every timestep t .

$$GHG_{Source,t} = GHG_{Sink,t} \quad (40)$$

Emission sources in the process are grid electricity consumed in processing steps as well as H_2 discharged from storage, that was compressed using grid electricity some time earlier.

$$GHG_{Source,t} = E_{Grid,t} \cdot CI_{grid} + m_{H_2,St \rightarrow Syn,t} \cdot CI_{H_2,St \rightarrow Syn,t} \cdot LHV_{H_2} \quad (41)$$

Emission sinks can either be expressed as mass flow or el. energy specific as shown in Equation (42) and (43) respectively.

$$GHG_{Sink,t} = m_{H_2,Co \rightarrow St,t} \cdot CI_{H_2,St \rightarrow Syn,t} \cdot LHV_{H_2} + m_{NH_3,t} \cdot CI_{NH_3,t} \cdot LHV_{NH_3} \quad (42)$$

$$GHG_{Sink,t} = E_{Co,grid,t} \cdot CI_{grid} + E_{syn,grid,t} \cdot CI_{grid} + m_{H_2,St \rightarrow Syn,t} \cdot CI_{H_2,St \rightarrow Syn,t} \cdot LHV_{H_2} \quad (43)$$

5.2 Rule-Based Dispatch Logic

The model itself has infinite possible operating points when considering all P2A process units. In a linear programming optimization, the models operating points are determined numerically with the goal to maximize or minimize one or more predefined objective functions.

As explained in chapter 2.3 this approach was not deemed feasible for modelling the emission tracking necessary for RFNBOs, especially with regards to storing H_2 of different CIs in the H_2 storage tank. The proposed alternative is a rule-based dispatch logic, where operating points are determined based on a set of conditional arguments that are parsed for every iteration of the simulation, resulting in one of N distinct operating modes for the plant. Operating points for all P2A process units are determined, depending on RES availability, BESS and H_2 storage levels and overall operational constraints defined in the model. The dispatch logic will be explained in the following section.

Generally, the logic describes the following four different operating modes, that are then further divided as is shown in Figure 12:

- Surplus operation, meaning there is more el. energy available from RES sources than is needed to operate the Haber-Bosch at nominal production rate, without the use of stored H₂ or electricity.
- Part load operation, meaning there is enough RE available, that, together with the maximum possible amount of added grid electricity, the Haber-Bosch can operate within its operational window, without the use of stored H₂ or electricity.
- Storage assisted operation, meaning the Haber-Bosch can operate at minimum load with the use of stored H₂ and/or electricity.
- Shut down operation, meaning there is not enough RE and stored H₂ and/or electricity available to operate the Haber-Bosch at the required minimum load, subsequently shutting it down. The AEL may however still operate and produce H₂ directly to storage. This also applies, if the restart delay restriction is still active.

A detailed description of the dispatch logic displayed in Figure 12 is provided in Appendix C.

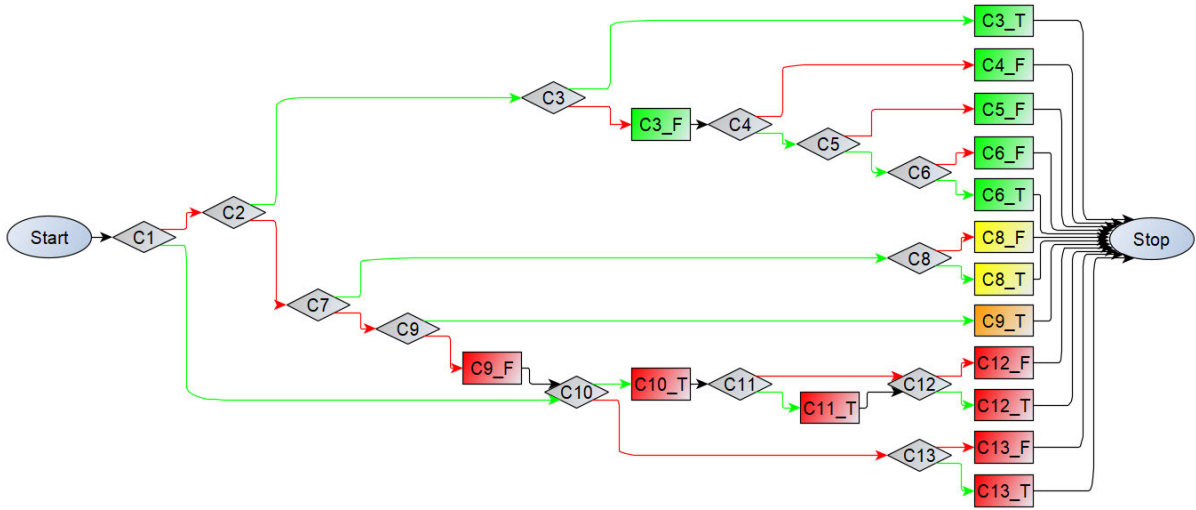


Figure 12: Model decision tree parsed through for every iteration: diamonds represent true-false conditions; red lines - false, green lines - true; squares represent operation decisions influencing P2A operating points. green - surplus operation, yellow - part load operation, orange - storage assisted operation, red - shut down operation

Surplus Operation (SO)

The plant operates in SO mode when the available RE supply exceeds the combined electricity demand of the Haber-Bosch synthesis unit operating at full capacity and the direct H₂ production via the electrolyzer (C2):

$$C2: E_{RES,t} \geq E_{plant,t}^{nom} = P_{Syn,nom} \cdot \Delta t \cdot \left(1 + \frac{SHC_{Syn} \cdot SEC_{El,t}}{SEC_{Syn}} \right) \quad (44)$$

In SO mode, the plant generally produces NH₃ at rated capacity (C3_F). As no grid electricity or stored H₂ is required, which could introduce GHG emissions, the NH₃ shows a carbon intensity of zero. C4, C5, and C6 determine in which order and to what extent RE, exceeding the demand of NH₃ production, is used to fill up BESS and H₂ storage. Priority is given to charging

H₂ storage because direct conversion to H₂ in the AEL is more efficient, than intermediate el. energy storage in BESS and subsequent H₂ conversion ($\eta_{\text{El}} > \eta_{\text{El}} \cdot \eta_{\text{BESS,roundtrip}}$).

In SO mode, the plant may produce NH₃ below rated capacity, in case storages are below the minimum required storage levels ($\text{SOC}_{\text{BESS,min}}$, $\text{SOC}_{\text{St,min}}$). The NH₃ production will be limited to minimum operational load until minimum storage levels are reached (C3).

Part Load Operation (PLO)

The plant operates in PLO mode, when the available RE together with its corresponding maximum possible share of grid electricity, exceeds the combined electricity demand of the Haber-Bosch synthesis unit operating at minimum capacity and the direct H₂ production via the electrolyzer (C7):

$$\text{C7: } \frac{E_{\text{RES},t}}{1 - \gamma_{\text{max}}} \geq E_{\text{plant},t}^{\text{min}} = \lambda_{\text{Syn,min}} \cdot E_{\text{plant},t}^{\text{nom}} \quad (45)$$

$$\gamma_{\text{max}} = \min \left(\frac{\text{SEC}_{\text{Syn}}}{\text{SEC}_{\text{Syn}} + \text{SHC}_{\text{Syn}} \cdot \text{SEC}_{\text{El},t}}, \frac{CI_{\text{budget}} \cdot LHV_{\text{NH}_3}}{CI_{\text{grid}} \cdot (\text{SEC}_{\text{Syn}} + \text{SHC}_{\text{Syn}} \cdot \text{SEC}_{\text{El},t})} \right) \quad (46)$$

The maximum share of grid electricity used in PLO mode is therefore determined by the minimum of two constraints (Equation (46)). The first constraint ensures that no grid electricity is consumed by the electrolyzer by limiting grid usage to the specific electricity consumption of the Haber-Bosch synthesis unit. The second constraint ensures compliance with the RFNBO carbon intensity threshold by limiting the allowable grid share based on the maximum admissible carbon intensity of the produced ammonia.

In PLO mode, the plant operates within the operational range of the Haber-Bosch process unit, depending on the effectively available RE and grid electricity. As with SO mode, the plant operation may be limited to minimal NH₃ production, until minimum storage level requirements are fulfilled (C8).

Storage Assisted Operation (SAO)

The plant operates in SAO mode when the available RE together with stored H₂ and/or electricity from BESS is enough to allow the Haber-Bosch unit to operate at minimum load (C9):

$$\text{C9: } E_{\text{RES},t} + E_{\text{BESS,out},t}^{\text{pot}} + m_{\text{H}_2,\text{St} \rightarrow \text{Syn},t}^{\text{pot}} \geq E_{\text{plant},t}^{\text{min}} \quad (47)$$

Condition C9 consists of three sub-conditions, which evaluate the available RE in relation to the minimum load requirements of the AEL and the Haber-Bosch synthesis units:

$$\text{C9-1: } E_{\text{RES},t} \geq (P_{\text{Syn,nom}} \cdot \lambda_{\text{Syn,min}} + P_{\text{El,nom}} \cdot \lambda_{\text{Syn,min}}) \cdot \Delta t \quad (48)$$

$$\text{C9-2: } P_{\text{Syn,nom}} \cdot \lambda_{\text{Syn,min}} \cdot \Delta t < E_{\text{RES},t} < (P_{\text{Syn,nom}} \cdot \lambda_{\text{Syn,min}} + P_{\text{El,nom}} \cdot \lambda_{\text{Syn,min}}) \cdot \Delta t \quad (49)$$

$$C9-3: E_{RES,t} \leq P_{Syn,nom} \cdot \lambda_{Syn,min} \cdot \Delta t \quad (50)$$

Each condition leads to a unique procedure to determine whether the available storage levels are sufficient to sustain minimum load operation of the plant. Hereby, H₂ discharge from storage is prioritized over discharging from the BESS, since H₂ can only be used to supply the Haber-Bosch synthesis unit, whereas el. energy from the BESS can support both the AEL and the Haber-Bosch processes to maintain continuous NH₃ production.

Shutdown Operation (SDO)

The plant may operate in SDO for one of two reasons. Either the available storage levels are insufficient to support minimum load operation (C9), or the Haber-Bosch synthesis unit has been recently shut down and is still within the restart delay period (C1). In either case, no NH₃ production takes place. Instead, available renewable electricity can be used to replenish the storage systems. Priority is given to first restoring the minimum storage levels of the BESS, followed by the H₂ storage. Once minimum levels are achieved, maximum charging of the H₂ storage is prioritized before continuing with the charging of the BESS.

5.3 KPI Evaluation

KPIs are calculated from plant operational data collected throughout the simulation and plant configuration inputs. Core KPI is the resulting levelized cost of ammonia (LCOA).

LCOA is calculated as described in chapter 2.4 using Equation (8). The LCOA is calculated on a monthly basis, meaning costs and produced ammonia are derived from monthly aggregated mass and energy flows. Costs and produced ammonia will be discounted using the WACC to account for the time value of money:

$$LCOA = \frac{\sum_{t=0}^n \frac{C_{CapEx,t} + C_{Replacement,t} + C_{O\&M,t} + C_{RES,t} + C_{Grid,t} - R_{Surplus,t}}{(1 + WACC_{month})^t}}{\sum_{t=0}^n \frac{A_t}{(1 + WACC_{month})^t}} \quad (51)$$

with

n	Total number of months (project lifetime x 12)
t	Month index
$WACC_{month}$	Monthly discount rate $WACC_{month} = (1 + WACC_{year})^{\frac{1}{12}} - 1$
$C_{CapEx,t}$	Capital expenditures, distributed through construction phase
$C_{Replacement,t}$	Replacement costs at predefined intervals (AEL stacks every 7 years, BESS every 10 years)
$C_{O\&M,t}$	Operation and maintenance costs, CPI-adjusted
$C_{RES,t}$	Monthly renewable electricity costs (fixed PPA price and RE production)
$C_{Grid,t}$	Monthly grid electricity costs (fixed grid price and grid consumption)
$R_{Surplus,t}$	Revenues from sales of surplus RE
A_t	Monthly ammonia production

Additional KPIs besides the LCOA used to assess technical feasibility and commercial viability of a simulated P2A plant configuration are summarized in Table 7.

Table 7: KPI overview of the P2A simulation model

<i>Type</i>	<i>KPI</i>	<i>Unit</i>
Plant operation	Average annual ammonia production	t _{NH₃} /a
	Average annual ammonia CI	gCO ₂ eq/MJ/a
	Average annual Haber-Bosch utilization	FLH
	Average annual electrolysis utilization	FLH
Electricity	Average annual RES availability	FLH
	Average annual RE production from PPA	MWh/a
	Average annual RE consumed onsite	MWh/a
	Average annual RE surplus	MWh/a
	Total share of surplus electricity	% _{RES}
	Average annual grid electricity consumption	MWh/a
	Specific cost of produced RE	EUR/MWh
	Specific cost of consumed RE	EUR/MWh
	Specific cost of consumed RE + grid	EUR/MWh
Shut down behaviour	Average annual No. of electrolysis shutdowns	1
	Average electrolysis shutdown duration	h
	Average annual electrolysis downtime	h
	Average annual No. of Haber-Bosch shutdowns	1
	Average Haber-Bosch shutdown duration	h
	Average annual Haber-Bosch downtime	h

5.4 Model Implementation Using Python

The simulation model was developed using the Python programming language, version 3.13. Programming and code management were carried out within the open-source integrated development environment (IDE) PyCharm, provided by JetBrains.

Several additional Python libraries were employed to develop the simulation model. In particular, `pandas` and `numpy` were used for efficient handling and processing of large time-series datasets. The `xlwings` library was utilized to establish a dynamic interface between the Python model and Microsoft Excel. Furthermore, `matplotlib` was applied to create detailed visualizations for both intermediate model outputs and final KPI evaluations.

The core functions constitute the primary modules of the simulation model. They handle the initialization, dynamic calculation and KPI evaluation of the P2A system.

- **`core_plant_init(**kwargs) → plant_config`**
The `core_plant_init` function initializes the complete plant configuration. It allows for flexible key-word argument (`**kwargs`) inputs, which are defined with internally stored default values. The function returns a structured dictionary (`plant_config`), that contains all parameters required for the P2A model, including:

- RES time series and corresponding fixed-price PPAs,
 - Grid electricity characteristics such as CI and electricity pricing,
 - Specifications of the core processing units (electrolyzer, Haber-Bosch synthesis, BESS, hydrogen storage, compressor),
 - Specific investment and operational cost parameters,
 - General input settings relevant for plant operation and economic evaluation.
- **core_plant_calc(plant_config) → df_out**
The `core_plant_calc` function executes the hourly operational simulation of the plant based on the provided configuration (`plant_config`). For every hourly iteration, the function is parsing through the decision tree in Figure 12 and determines the operational mode of the P2A model. It models the interaction between RE availability, storage behaviour (BESS and hydrogen storage), process unit dynamics and compliance with operational constraints. The function returns a detailed time series output (`df_out`) containing hourly values for all relevant physical and operational variables, including energy flows, storage states, production volumes and operation modes.
 - **core_KPI_calc(plant_config, df_out) → KPI_out**
The `core_KPI_calc` function evaluates the KPIs described in chapter 5.3 based on the plant configuration and the operational output. The output (`KPI_out`) consolidates these KPIs into a structured format for further evaluation and visualization.

Multiple ‘main’ scripts are programmed, that make use of the three core functions to generate results for either one specific plant configuration, or multiple configurations to show sensitivities of up to three input parameters simultaneously (`main_senario_calc.py`, `main_sensitivity_1D.py`, `main_sensitivity_2D.py`, `main_sensitivity_3D.py`).

To calculate a single scenario over a 20-year operational project lifetime, the model requires approximately 7 to 9 seconds of computation time and generates around 65 MB of operational output data (`df_out.csv`). Both the calculation time and the amount of generated data scale linearly with the number of scenarios evaluated. Therefore, during sensitivity analyses involving multiple scenarios, only the input configurations (`plant_config`) and resulting KPI data (`KPI_out`) are stored. This significantly reduces the data storage requirements to approximately 15 to 20 KB per scenario, enabling efficient handling of large scenario sets without excessive memory or storage demand.

To visualize results, there are multiple ‘visualization’ scripts available, that load in stored data and generate plots. The modular structure of separating simulation and visualization is implemented due to high cumulative computation times, especially for high resolution sensitivities.

5.5 Plausibility Test

A series of test simulations were performed to check for consistent model implementation and assess the plausibility of the generated simulation results.

5.5.1 Simulation Using Test Data

The proper implementation of the simulation model, as described in chapters 5.1 and 5.2, was assessed using test data. A synthesised renewable energy time series was used as input. The RE time series was designed, so that the model iterates through its distinct operational modes (SO, PLO, SAO, SDO). The resulting simulation time series, that represents the P2A models' response to the test data input, is visualised in Figure 13.

Plot (A) shows the supply and consumption of el. energy. The supply of RE (test data), grid electricity and discharged BESS electricity is shown in negative y-direction. The consumption in P2A processing units and leftover surplus volumes are plotted in positive y-direction. Plot (B) shows the charging and discharging of the BESS, as well as the time varying state of charge. Additionally, the maximum storage capacity (green dotted line) and the minimum storage level requirement threshold (red dotted line) are included in the plot. Effects of BESS charging and discharging efficiencies on the el. energy balance are also included. Equivalent to plot (B), plot (C) shows the charging and discharging behaviour of the H₂ storage tank, as well as its time varying state of charge. Plot (D) visualizes the tracking of carbon emissions associated to H₂ entering and leaving the H₂ storage tank. Further, the specific average carbon intensity of H₂ stored in the tank is displayed. Plot (E) shows el. energy consumption in the Haber-Bosch processing unit differentiated by source and the total ammonia production rate (red line). Green bars represent consumption of fully renewable electricity either directly from the RES, or from BESS. Yellow bars represent consumption of grid electricity. Lastly, plot (F) shows the specific carbon intensity of produced NH₃ volumes. For reference the RFNBO emission threshold, as well as the predefined emission budget are included in the plot. All six plots are synchronized on a shared hourly x-axis attached to plot (F).

In the following section, Figure 13 will be examined in detail. A chronological walkthrough of the test simulation period highlights the operational modes of the P2A plant, the evolution of storage levels, and the resulting CIs of the produced ammonia.

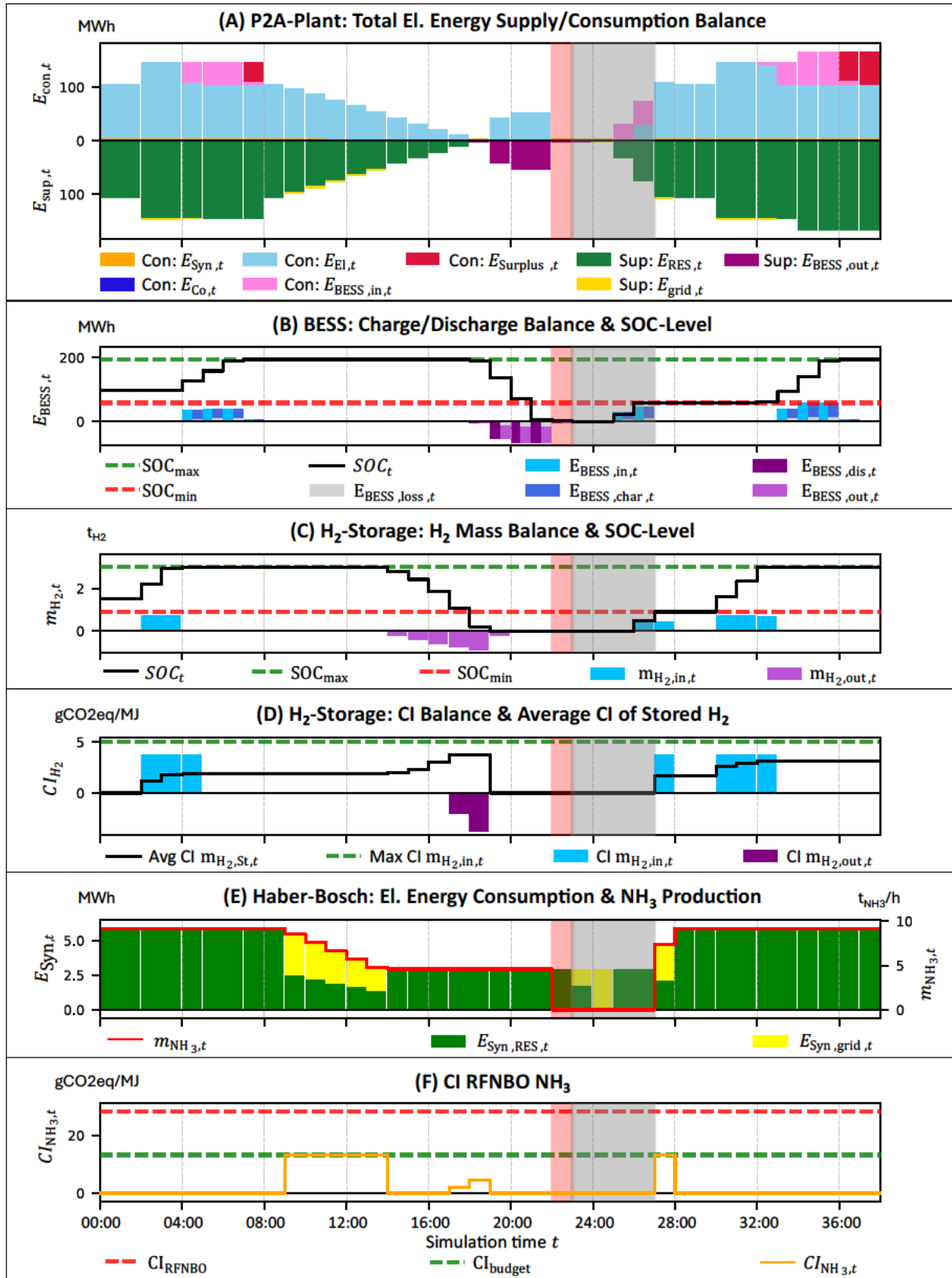


Figure 13: Time series visualization of P2A simulation using renewable energy test data

Timestep 00:00 to 02:00: Supplied RE from RES asset allows for unassisted operation of the P2A plant at full capacity. Haber-Bosch H₂ demand can be supplied in full directly from AEL.

BESS and H₂ storage are unaffected. No carbon emissions are incorporated into the produced NH₃, as no grid electricity is consumed. Subsequently the produced NH₃ shows a carbon emission intensity of 0 gCO₂eq/MJ and is therefore RFNBO compliant ($CI_{NH_3,t} < 28.2$ gCO₂eq/MJ).

Timestep 02:00 to 09:00: The plant is in SO mode. The RES asset is supplying more RE, than is necessary to operate the Haber-Bosch at full capacity. The excess RE is transferred to storage. Both H₂ storage and BESS are above the required minimum storage levels. Subsequently, RE is initially used to produce additional H₂ that is transferred to storage. To maximize RE utilization, the compressor is running on grid electricity. Consequently, the H₂ volumes entering the storage tank show a CI larger than zero. This leads to an increase of the weighted average CI of stored H₂. Once the H₂ storage is full, the BESS is charged to its maximum. After both storages are at full capacity, excess RE will be denoted as surplus (plot (A) red bar). Surplus electricity will either be sold off at the spot market, or, in case no resale is considered, will be curtailed. Since no grid electricity or H₂ from storage is processed in the Haber-Bosch, the CI of produced ammonia is 0 gCO₂eq/MJ (RFNBO compliant).

Timestep 09:00 to 14:00: The plant is in PLO mode. The maximum possible share of grid electricity is included into the consumption of the Haber-Bosch. Supplied with RE directly from the RES asset, the AEL can produce enough H₂ for the Haber-Bosch to operate above its minimum load. Storage capacities are not accessed. The amount of grid electricity added to the Haber-Bosch consumption is limited by the available CI budget. As observed in the test simulation, grid electricity emissions are too high, for the entire Haber-Bosch consumption to be supplied by grid. Consequently, the CI of the produced NH₃ reaches the upper limit defined by the CI budget. Adding in additional grid electricity may still yield NH₃ with a CI below the RFNBO threshold. However, this would reduce the available CI margin for downstream processes, risking the RFNBO compliance further down the line.

Timestep 14:00 to 22:00: The plant is in SAO mode. The available RE from supplied from RES asset is not enough to ensure operation of Haber-Bosch at minimum load. Missing energy is drawn from storage. At first hydrogen is drawn from the H₂ storage tank. According to the FIFO approach, the CI of the initial H₂ volumes drawn from storage is zero. Once the H₂ batches, that were stored during timestep 02:00 to 05:00, are (partially) fed to the Haber-Bosch, the associated CI of H₂ and NH₃ increases depending on the drawn batch composition. The BESS is accessed after the available H₂ storage capacity is depleted. Once, solely BESS supplies AEL and Haber-Bosch, the associated NH₃ CI goes down to zero again. At this point neither grid electricity nor stored H₂ introduce emissions into the production.

Timestep 22:00 to 27:00: There is no supply from RES and remaining BESS capacity is insufficient to enable Haber-Bosch operation at minimum load. The Haber-Bosch process is forced to shut down (red area at timestep 22:00). Ammonia production rate drops to zero. A reduced restart timer of four hours is initialized. The plant continuous to operate in shut down mode (SDO), highlighted by the grey area across plots (A) to (F). The electrical standby demand of the Haber-Bosch processing unit, that occurs during shutdown mode, is covered by RE from RES and BESS. If both are not available grid electricity is drawn. Once RE is available again, and the Haber-Bosch is still in restart delay, storages are replenished. At first BESS is recharged to required minimum storage levels, followed by H₂ storage. During shutdown restart, no grid consumption is allowed, with the exemption of Haber-Bosch standby demands. This

means H₂ is compressed to storage using RE. Consequently, H₂ batches added to storage show zero gCO₂eq/MJ.

Timestep 27:00 to 30:00: The restart timer of the Haber-Bosch has run out and the process may restart. As in timestep 00:00 to 02:00, the RES asset supplies exactly enough RE to theoretically operate the Haber-Bosch plant at nominal load without storage assistance or grid incorporation. Though, H₂ storage has not yet reached its required minimum storage level. The ammonia production rate is therefore limited to minimum load, until both BESS and H₂ storage are recharged to minimum storage levels. Once minimum storage levels have been reached, the NH₃ production commences at nominal load with no grid or storage assistance, yielding a CI of zero gCO₂eq/MJ.

Timestep 30:00 to 38:00: The plant is in SO mode again. Supplied RES surpasses the required demand to operate the Haber-Bosch at full capacity. Excess RE is deferred to storage. First the H₂ storage tank is recharged, followed by the BESS. Subsequently remaining RE is denoted as surplus.

The test simulation shows full implementation according to the model description in chapters 5.1 and 5.2. The test shows, that the model responds to changes in RE availability in line with the formulated operating modes and ensures RFNBO compliant NH₃ production. KPIs derived from calculated P2A time series should therefore be assumed to be plausible within the defined scope of the model.

5.5.2 Boundary Tests

To assess the model's boundary behaviour three test simulations were performed. Each simulation was performed for a simulation time of one year:

Table 8: Overview of boundary simulation test setups and expected outcomes

Test	Description	Expected results
No RES	RES asset with capacity factor 0 No storage	No ammonia production
Full RES	RES asset with capacity factor 1 No storage	Continuous ammonia production at nominal load
Max storage	Typical Wind/PV RES combination Oversized storage	Fluctuating ammonia production with no Haber-Bosch shut-downs

The "No RES" and "Full RES" test resulted in continuous operation in one operation mode. The results of the "No RES" test show shut down operation mode for the entire simulation time. No ammonia is synthesized, as no renewable electricity is available. Haber-Bosch standby consumption is drawn from grid electricity. "Full RES" simulation shows continuous operation in the part load operation mode. There is no grid electricity integration to the Haber-Bosch consumption, since RES is sized up to exactly cover the nominal electricity and H₂ demand of the Haber-Bosch. Both Haber-Bosch and the AEL show perfect utilization at 8760 FLHs.

Figure 14 shows the simulation time series for the “Max storage” boundary test. As expected, oversized storage capacity (BESS: 4000 MWh, H_2 storage: 80 t_{H_2}) ensures uninterrupted ammonia production. No Haber-Bosch shutdowns occur. Looking at the storage levels of H_2 storage and BESS highlights the implementation of storage capacity dispatch. Since stored H_2 is prioritized above el. energy from BESS, the utilization of BESS is limited to situations, where H_2 storage capacity is already depleted. This results in low utilization of the BESS for large scale storage systems consisting of BESS and H_2 storage. Additionally, storage capacity can only be used to avoid Haber-Bosch shutdowns by ensuring minimum operational load during SAO mode. Ammonia yield maximization during PLO is not considered in the model.

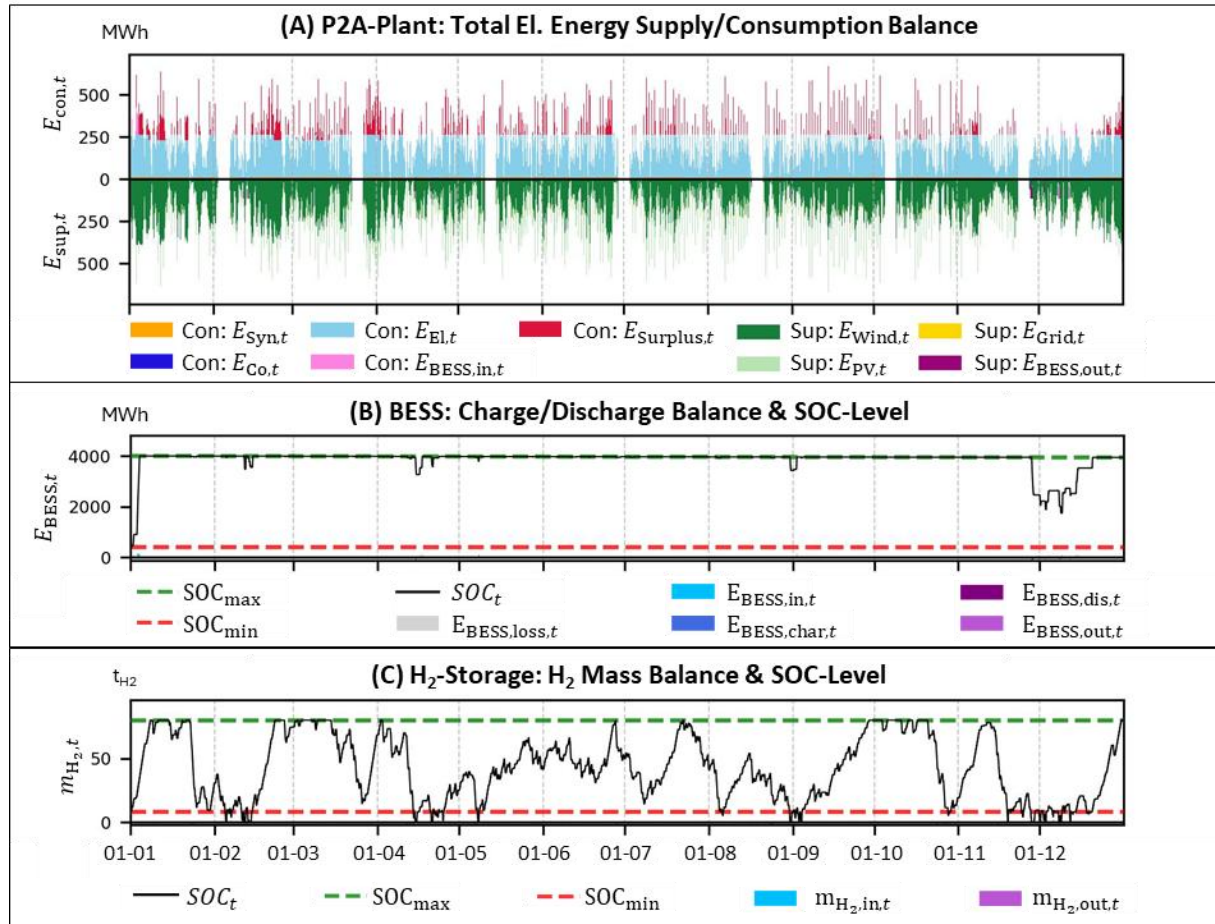


Figure 14: “Max storage” boundary test simulation results.

All boundary tests concluded as expected. This further strengthens confidence in the model to deliver plausible results.

6 Results

The following chapter presents the results of a sensitivity analysis conducted on renewable energy supply and storage capacity to assess their impact on the commercial and operational performance of P2A system.

6.1 Availability of Renewable Electricity

The effects of differing renewable electricity availability on the commercial and technical performance of P2A processes is presented in the following section. To generate comparable results, most variable inputs are constant for every simulation, if not otherwise stated. This includes all technical, commercial and operational assumptions derived in chapter 4 and summarized in Table 6. Grid emissions intensity is assumed constant with 114 gCO₂eq/MJ.

The alkaline electrolyzer has a rated power of 250 MW, producing 4.5 t_{H₂} per hour at initial efficiency. The Haber-Bosch process has a rated capacity of 20 t_{NH₃} per hour, consuming 3.9 t_{H₂} per hour at nominal production rate. The BESS is sized to 200 MWh capacity with 200 MW rated power. The H₂ storage is set to 50 t_{H₂} capacity. Based solely on hourly hydrogen demand, BESS and H₂ storage combined allow for 27 hours ammonia production at Haber-Bosch minimum load. The total initial CapEx is 468 MEUR (without replacement costs).

Wind and PV assets described in Table 4 were assessed in four combinations. For each combination of high and low yield locations sensitivities on the rated power of contracted wind and PV assets were simulated. Detailed KPI overview for each combination of wind and PV is provided in Appendix D.

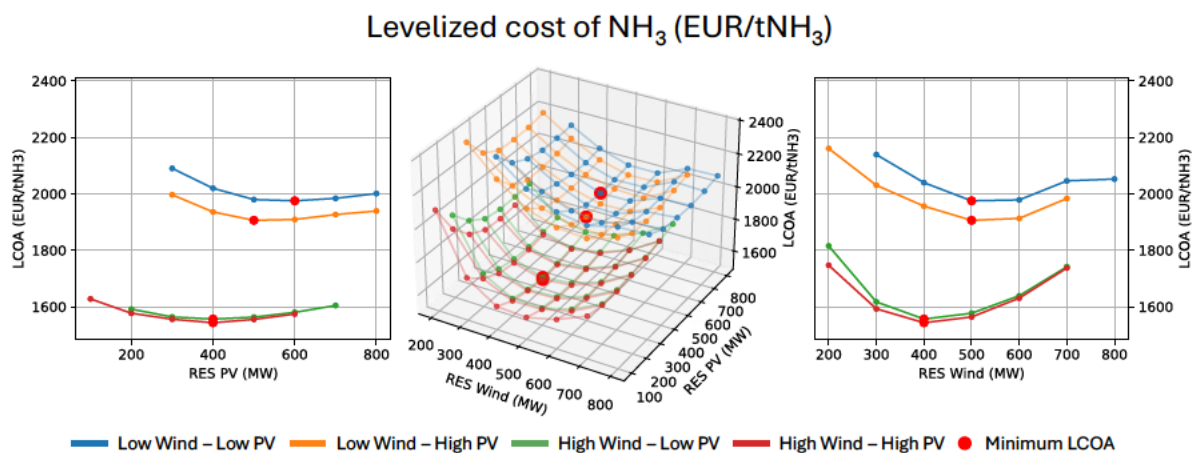


Figure 15: (centre) LCOA evaluation for all simulated RES combinations. (left) and (right) show LCOA sensitivity to PV and wind capacity, respectively, each evaluated along the axis intersecting the minimum LCOA.

Results

Figure 15 (centre) shows a scatter plot of the LCOA resulting from each P2A simulation, as a function of installed wind and PV capacities. The left and right subplots depict one-dimensional sensitivity analyses: the left plot shows the variation of LCOA with PV capacity at the wind capacity corresponding to the minimum LCOA, while the right plot shows the variation with wind capacity at the respective optimal PV capacity. For each combination of wind and PV assets a minimum LCOA could be found. The combination of high-wind and high-PV show the lowest overall LCOA for the simulated P2A plant (red grid). The combination of low-wind and low-PV show the highest LCOA. This is expected, especially when considering the underlying PPA electricity price assumptions for additionality compliant RES assets, explained in chapter 4.1.1. The difference between low and high PV in combination with high-wind is marginal with only a 0.8 % increase in LCOA when using low-PV. This effect becomes more prevalent when looking at combinations of low-wind with PV. Here a cost increase of 3.6 % can be observed for using low-PV. Further the required installed capacity increases when using low yield RES assets. The combined RES to AEL power ratio for high yield and low yield combinations is at 3.2 and 4.4, respectively. Generally, the influence of supplying wind assets on the LCOA is higher than that of PV assets.

Figure 16 shows the cost structure of the minimum LCOA for each wind-PV configuration. The total LCOA ranges from 1,554 EUR/t_{NH₃} in the high-wind, high-PV case to 1,989 EUR/t_{NH₃} in the low-wind, low-PV scenario. The most significant cost driver across all configurations is the cost of electricity procured via RES PPAs, which accounts for more than half of total LCOA in each case. The initial CapEx and replacement costs contribute between 410–521 EUR/t_{NH₃} and 116–148 EUR/t_{NH₃}, respectively. Grid electricity usage remains limited across all configurations due to RFNBO compliance constraints, which permit grid consumption exclusively for the Haber-Bosch synthesis and hydrogen compression. Consequently, the associated cost contribution does not exceed 37 EUR/t_{NH₃}, observed in the high-wind, low-PV scenario. There are no resale revenues, since the resale price of surplus electricity is assumed to be zero.

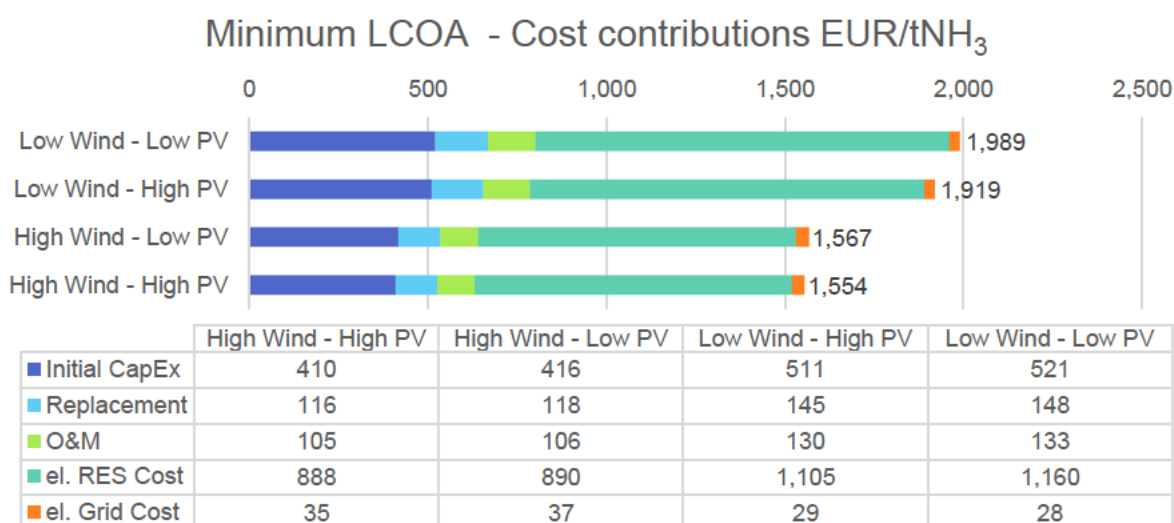


Figure 16: Cost composition of the minimum LCOA for four representative wind–PV supply configurations. Values are split into CapEx, replacement, O&M, renewable and grid electricity cost contributions

Results

Table 9 summarizes the evaluated KPIs of the simulations achieving minimum LCOA for each wind-PV combination. Notably is here once again the low share of grid electricity consumption across all combinations with 1.5–2.0 % of total electricity consumption. Combinations with high-RES yield assets show higher grid usage shares, which can be attributed to more instances of part load operation mode, where grid electricity can be supplemented in the Haber-Bosch electricity consumption. Average carbon emission intensity of produced ammonia increases proportionally with the increase of grid electricity usage. Overall average ammonia CI is well below the required 28.2 gCO₂eq/MJ with 3.37–5.03 gCO₂eq/MJ. Maximum NH₃ CI is at 13.97 gCO₂eq/MJ for all combinations leaving more than half the emission budget for further downstream processes, such as transport or ammonia cracking to release elemental hydrogen. This shows that even at maximum grid incorporation during part load operation mode, the maximum CI budget of 22.2 gCO₂eq/MJ (equation (35)) is not fully utilised.

The specific cost of fully renewable electricity sourced from contracted wind and PV assets ranges from 59.6 to 73.6 EUR/MWh, with lower costs observed in high-yield wind-PV combinations. These values represent the weighted average cost, calculated based on asset-specific PPA prices and actual renewable energy production. To better reflect the effective cost of electricity actually used in the process, the specific cost of consumed renewable electricity accounts for the share of unused surplus energy. In this approach, the total cost of contracted renewable electricity is allocated only to the portion that is effectively utilized. When grid electricity is also considered, the result is the effective specific electricity cost, which reflects a combined cost of both renewable and grid electricity. In this case, configurations with low-wind and low-PV exhibit the highest costs, reaching up to 96.5 EUR/MWh, whereas high-wind, high-PV setups achieve the lowest effective cost at 75.4 EUR/MWh.

Table 9: Overview of evaluated KPIs at minimum LCOA for each wind-PV combination

<i>KPI</i>	<i>Unit</i>	<i>L Wind L PV</i>	<i>L Wind H PV</i>	<i>H Wind L PV</i>	<i>H Wind H PV</i>
RES Wind	MW	500	500	400	400
RES PV MW	MW	600	500	400	400
Minimum LCOA	EUR/tNH ₃	1,975	1,906	1,556	1,543
Total CapEx	MEUR	468	468	468	468
Avg annual NH ₃ production	ktNH ₃ pa	100	102	126	128
Avg annual NH ₃ CI	gCO ₂ eq/MJ	3.37	3.54	5.18	5.03
Max NH ₃ CI	gCO ₂ eq/MJ	13.97	13.97	13.97	13.97
Avg annual Haber-Bosch FLH	FLH	5,024	5,117	6,324	6,421
Avg annual Electrolysis FLH	FLH	4,661	4,747	5,869	5,959
Avg annual RES FLH	FLH	1,447	1,586	2,297	2,401
Avg annual RES production	GWh	1,592	1,586	1,838	1,921
Avg annual RES consumed	GWh	1,223	1,245	1,523	1,547
Avg annual RES surplus	GWh	368	342	315	374
Avg annual Grid consumption	GWh	18.8	19.9	31.1	30.1
Total RES + Grid consumption	GWh	24,842	25,289	31,079	31,542

Results

KPI	Unit	L Wind	L Wind	H Wind	H Wind
		L PV	H PV	L PV	H PV
RES share total consumption	%	98.5	98.4	98.0	98.1
Grid share total consumption	%	1.5	1.6	2.0	1.9
Curtailment	%	23.1	21.5	17.1	19.4
Specific cost of produced RES	EUR/MWh	73.6	71.6	61.4	59.6
Specific cost of consumed RES	EUR/MWh	95.7	91.3	74.1	74.0
Specific cost of consumed RES + Grid	EUR/MWh	96.5	92.2	75.7	75.4
Avg annual Nr of AEL Shutdowns	1	90.9	90.0	37.6	35.8
Avg AEL Shutdown Duration	h	8.5	8.9	9.7	10.0
Avg annual AEL downtime	h	772	798	364	357
Avg annual Nr of HB Shutdowns	1	33.0	31.2	14.2	12.8
Avg HB Shutdown Duration	h	49.0	49.0	49.2	49.0
Avg annual HB downtime	h	1,613	1,529	696	627

Across all combinations of wind and PV the share of unused surplus electricity increases with additional installed RES capacity, as can be seen in Figure 17. It can be observed that low-PV in combination with high wind consistently results in lower surplus rates, than high-wind paired with high PV (red and green grid). For low-wind the opposite applies, where the combination with high-PV yield lower rates than low PV (blue and orange grid). While sensitivities on PV yield a steady rise of surplus rates for all combinations of wind and PV, the sensitivities to wind vary more distinctly. Here high wind combinations show sharper rate of increase than those for low-wind ones. At the RES configurations that minimize the LCOA for each combination, the surplus share ranges from 17.1% to 23.1%. The lowest surplus occurs in the high-wind, low-PV case (green), while the highest is observed for low-wind, low-PV (blue).

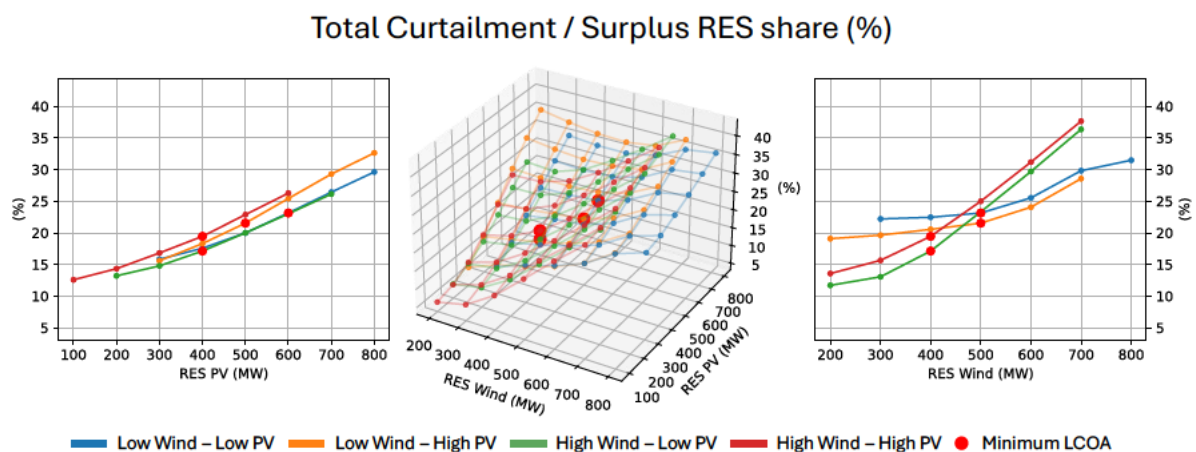


Figure 17: (centre) share of surplus electricity evaluation for all simulated RES combinations. (left) and (right) show surplus sensitivity to PV and wind capacity, respectively, each evaluated along the axis intersecting the minimum LCOA

As mentioned earlier the incorporation of grid electricity in the model is restricted to the Haber-Bosch process and the compressor. This generally leads to low shares of grid electricity in the

overall electricity consumption. Figure 18 shows that the higher the contracted total RES capacity, the lower the share of grid electricity usage. This is in line with the notion, that grid electricity consumption is an indicator of P2A operation under part load, as high-RES capacities shift the P2A process towards operating in surplus mode. Conversely for total RES capacities below even the rated nominal load of the P2A plant ($P_{\text{Syn,nom}} + P_{\text{El,nom}}$), the operation mode shifts from part load operation towards storage assisted or even shut down operation mode. The wind sensitivity exhibits maximum grid shares at around 300 MW wind capacity for high wind combinations and 400 and 500 MW for low wind combinations with high and low PV, respectively. This indicates that at those capacities the part load operation incidence rate is at its maximum for the respective wind-PV combinations. The PV sensitivity points towards similar maximum behaviour only visible at lower capacities.

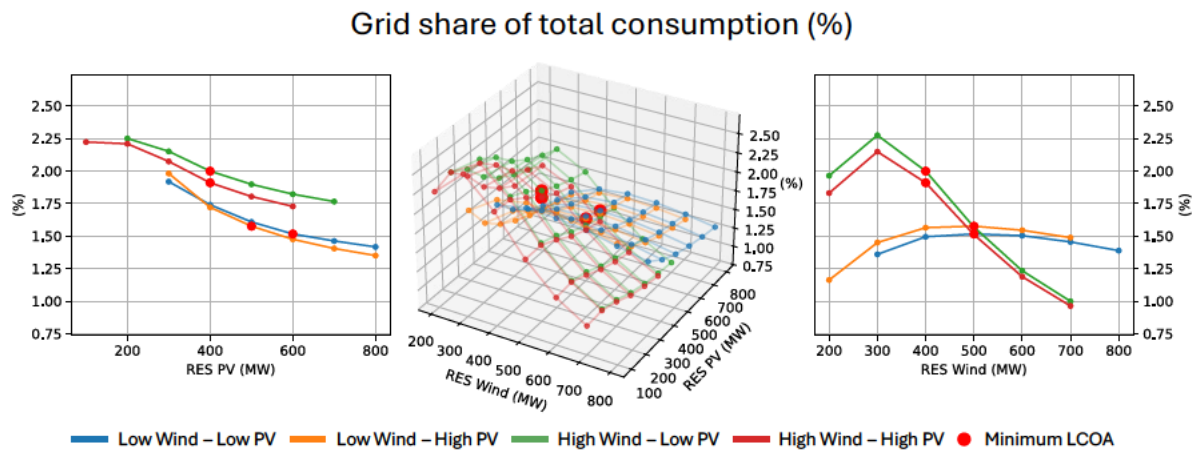


Figure 18: (centre) grid share evaluation for all simulated RES combinations. (left) and (right) show grid share sensitivity to PV and wind capacity, respectively, each evaluated along the axis intersecting the minimum LCOA

Figure 19 shows the average annual ammonia production for each simulated wind-PV configuration. As could be expected, the more RES capacity is contracted, the higher the annual ammonia production. Though the rate of increase reduces continuously the more RES capacity is added. Hereby an increase of wind capacity results in a stronger increase in ammonia production, than adding PV capacity. Combinations of high wind and PV show annual production of up to 28% higher than combinations of low wind. Variation between high and low PV show little difference in annual production. Changing from low to high PV results in a production increase of only 2.0% and 1.6% in combination with low and high wind, respectively.

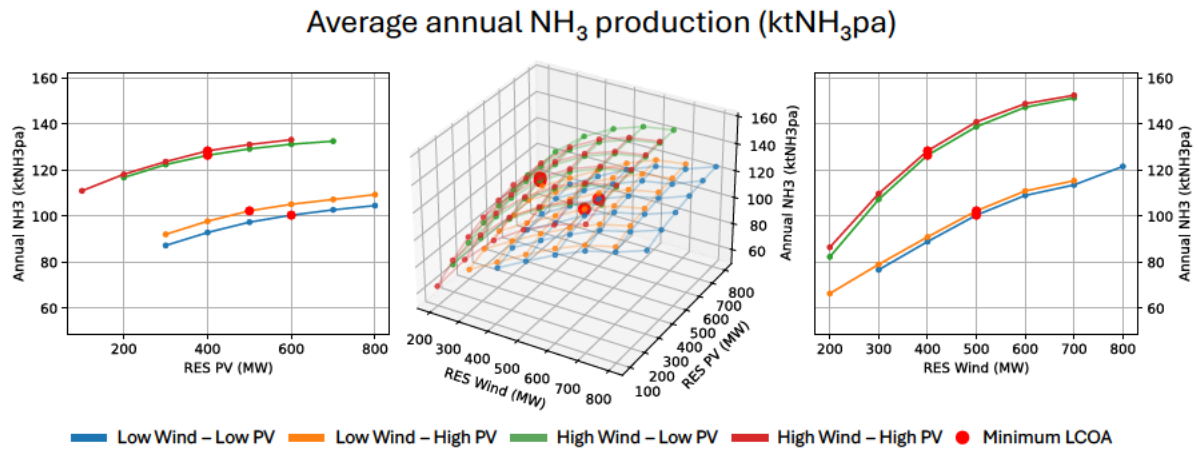


Figure 19: (centre) Average annual ammonia production for all simulated RES combinations. (left) and (right) show average annual ammonia production sensitivity to PV and wind capacity, respectively, each evaluated along the axis intersecting the minimum LCOA

Figure 20 shows an overview utilization and shutdown frequency for the Haber-Bosch processing unit and the alkaline electrolyzer.

At minimum LCOAs of each wind-PV combination the Haber-Bosch unit utilization ranges from 5024 to 6421 FLH. The sensitivity characteristics with respect to contracted wind and PV capacities are equivalent to those of annual ammonia production, since the efficiency of the modelled Haber-Bosch unit is constant for all operational levels. The same efficiency implementation applies for the modelled electrolyzer, resulting in again equivalent utilization dynamics for varying RES capacities. Electrolyzer utilization ranges from 4,661 to 5,959 FLH due to oversizing relative to Haber-Bosch capacity. AEL oversizing is implemented to enable effective use of H_2 storage, thereby minimizing operational shutdowns caused by the minimum load constraints of the Haber-Bosch process.

Shutdown frequencies for both Haber-Bosch and AEL decrease with increasing RES capacity. As with plant utilization, sensitivity characteristics of wind and PV capacities for both processing units are equivalent to each other. Adding wind capacity results in sharper decreases of shutdown frequencies for both low and high wind combinations, than adding PV capacity. Shutdown frequencies for the Haber-Bosch processing unit at minimum LCOA range from 12.8–33.0 shutdowns per year for the high-wind high-PV and low-wind low-PV combinations, respectively. Associated total downtime range from 627–1,613 hours per year. Based on average annual ammonia production and total downtime the average operational load for high-wind high-PV and low-wind low-PV combinations can be estimated to 70% and 79%. The AEL shows shutdown frequencies range from 35.8 to 90.9 shutdowns per year with an average duration of 8.5 to 10 hours. The average duration must be considered carefully though. If the Haber-Bosch process is forced to shut down and go into restart delay for 48 hours, the AEL can continue operating until the H_2 storage is fully recharged. With the selected storage capacity of 50 t_{H_2} this could be achieved within 11 hours, if the AEL is operating at nominal load. After that the AEL will be forced to shut down and remain turned off until the restart delay of the Haber-Bosch process is timed out.

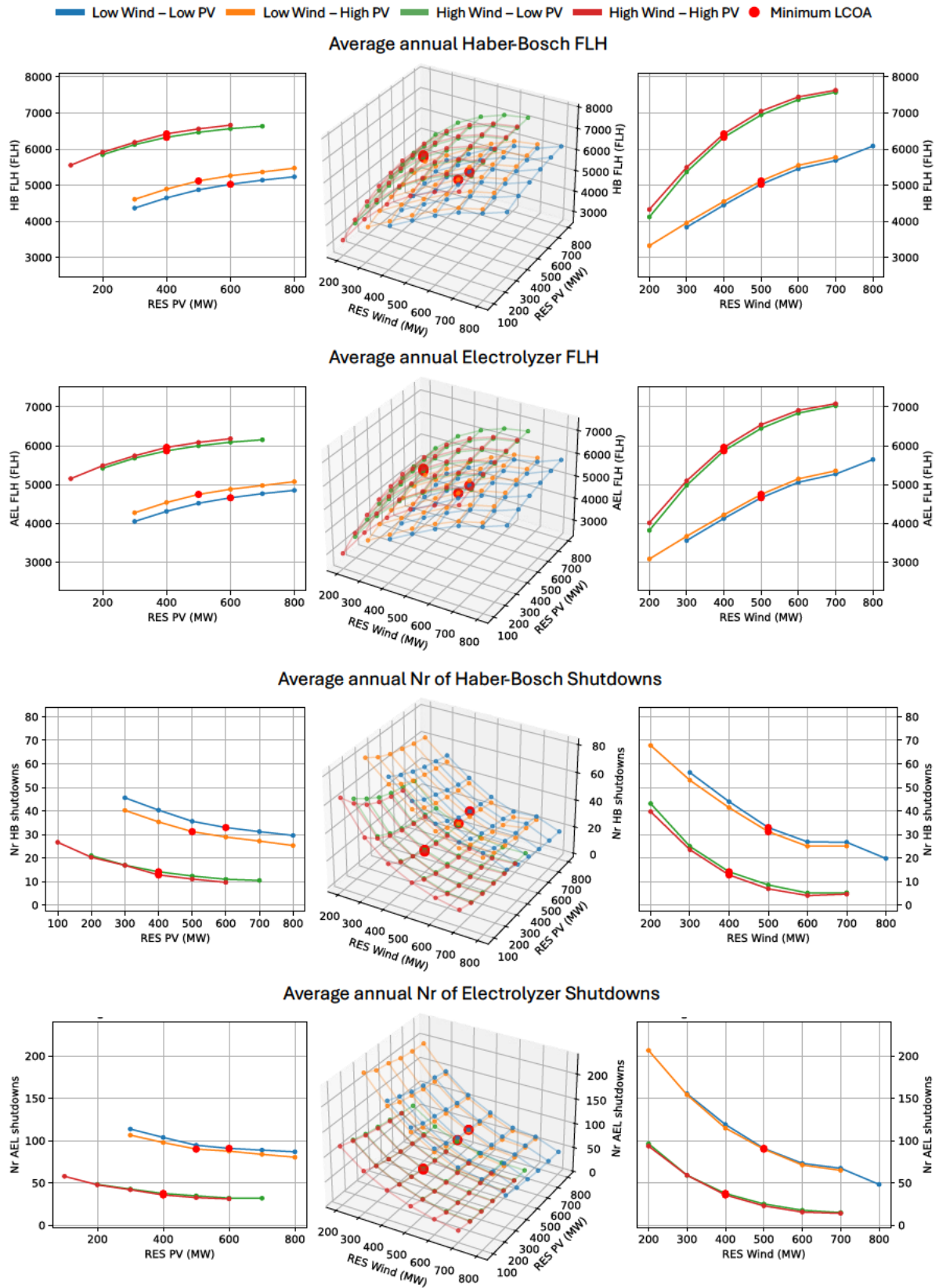


Figure 20: (centre) Overview of average annual FLH and number of shutdowns for Haber-Bosch processing unit and alkaline electrolyzer for all simulated RES combinations. (left) and (right) show sensitivity to PV and wind capacity evaluated along the minimum LCOA

6.2 Storage Integration

In the following section the results for P2A simulations with varying BESS and H₂ storage capacities will be presented. As with the variability of RES in the section before, most variable inputs will be constant to ensure comparability of results.

The alkaline electrolyzer has a rated power of 250 MW, producing 4.5 t_{H2} per hour at initial efficiency. The Haber-Bosch process has a rated capacity of 20 t_{NH3} per hour, consuming 3.9 t_{H2} per hour at nominal production rate. Again, a constant grid carbon intensity of 114 gCO₂eq/MJ is assumed.

The sensitivity of BESS capacity is evaluated for the range from 0 to 5,000 MWh in steps of 1,000 MWh. Maximum BESS capacity is enough to supply the hydrogen demand of the Haber-Bosch processing unit operating on minimum load for 46 hours. Rated nominal BESS power is constant with 200 MW across all simulated capacities. The sensitivity of H₂ storage capacity ranges from 0 to 100 t_{H2} in steps of 20 t_{H2}. At maximum capacity the H₂ storage can supply the minimum load hydrogen demand of the Haber-Bosch for 51 hours. Maximum compression rate of the storage feed compressor is determined post simulation. It is sized to fulfil the maximum occurring H₂ inflow to the storage tank.

Sensitivities of BESS and H₂ storage are evaluated for four distinct RES supply configurations. The four RES asset and capacity configurations yielding the lowest LCOAs in the RES sensitivity analysis of the previous chapter are chosen (see Table 9). Detailed KPI overview for each combination of wind and PV is provided in Appendix E.

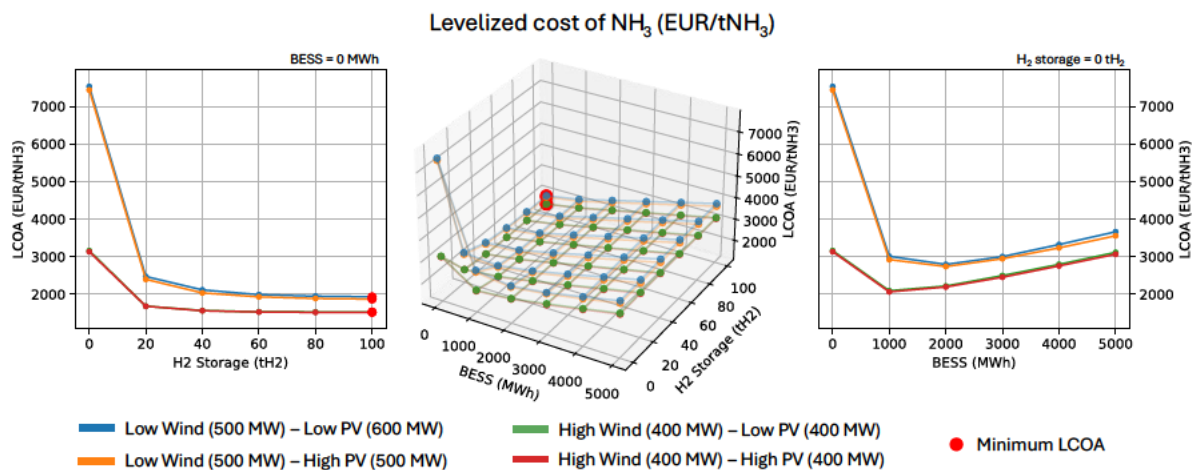


Figure 21: (centre) LCOA evaluation for all simulated storage combinations. (left) and (right) show LCOA sensitivity to BESS and H₂ storage capacity, respectively

Figure 21 illustrates the LCOA evaluation of all simulated storage combinations. The minimum LCOA for all wind-PV scenarios is located at maximum H₂ storage of 100 t_{H2} and no BESS capacity. LCOA minima range from 1,512–1,935 EUR/t_{NH3}. Low-wind scenarios show 24.0% and 26.4% higher minimum LCOA than high-wind scenarios when paired with high and low PV, respectively. For low capacities, both BESS and H₂ storage show a step drop in LCOA. This trend continuous for increasing H₂ storage capacities, al be it a lot shallower. With

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increasing BESS capacity, the downwards trend quickly reverses and LCOA start steadily increasing. These dynamics are equivalent for all four simulated RES scenarios.

Table 10 provides a detailed KPI evaluation of simulation runs yielding minimum LCOAs for the different wind-PV combinations assessed in the storage sensitivity. Compared to the minimum LCOAs derived in the RES sensitivity (see Table 9) a slight decrease in LCOA for all four RES combinations can be observed. The largest decrease can be observed for the low-wind low-PV combination where the improved storage configuration of H₂ storage yields a 2.0% decrease in LCOA. The lowest decrease is at the high-wind low-PV combination with 1.6%. Annual average ammonia production remains almost unchanged for all minimum LCOA configurations when compared with RES sensitivity minima. The doubling of H₂ storage capacity from 50 to 100 t_{H2} and removing of BESS system result in a decrease in initial CapEx by 6.6 % from 468 to 437 MEUR. Specific costs of consumed electricity show a slight increase compared to RES sensitivity minima LCOA. This implies less efficient use of delivered RE from RES assets, since the RES configurations for minimum LCOA yielding wind-PV combination are equal. This is further supported by the increase in curtailment rates. For low-wind low-PV the smallest increase from 23.1% to 23.8% can be observed. High-wind high-PV shows the largest increase from 19.4% to 20.6%.

Table 10: Overview of evaluated KPIs at minimum LCOA for each wind-PV combination

<i>KPI</i>	<i>Unit</i>	<i>L Wind L PV</i>	<i>L Wind H PV</i>	<i>H Wind L PV</i>	<i>H Wind H PV</i>
BESS capacity	MWh	0	0	0	0
H ₂ storage capacity	t _{H2}	100	100	100	100
Minimum LCOA	EUR/t _{NH3}	1,935	1,875	1,531	1,521
Total CapEx	MEUR	437	437	437	437
Avg annual NH3 production	ktNH3pa	100	101	125	127
Avg annual NH3 CI	gCO2eq/MJ	3.36	3.51	5.11	4.95
Max NH3 CI	gCO2eq/MJ	13.97	13.97	13.97	13.97
Avg annual Haber-Bosch FLH	FLH	4,981	5,053	6,243	6,327
Avg annual Electrolysis FLH	FLH	4,624	4,690	5,795	5,874
Avg annual RES FLH	FLH	1,447	1,586	2,297	2,401
Avg annual RES production	GWh	1,592	1,586	1,838	1,921
Avg annual RES consumed	GWh	1,213	1,230	1,504	1,526
Avg annual RES surplus	GWh	378	357	333	395
Avg annual Grid consumption	GWh	19.2	20.2	30.8	30.0
Total RES + Grid consumption	GWh	24,650	24,995	30,700	31,111
RES share total consumption	%	98.4	98.4	98.0	98.1
Grid share total consumption	%	1.6	1.6	2.0	1.9
Curtailment	%	23.8	22.5	18.1	20.6
Specific cost of produced RES	EUR/MWh	73.6	71.6	61.4	59.6
Specific cost of consumed RES	EUR/MWh	96.5	92.4	75.1	75.0
Specific cost of consumed RES + Grid	EUR/MWh	97.3	93.3	76.6	76.5

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KPI	Unit	L Wind	L Wind	H Wind	H Wind
		L PV	H PV	L PV	H PV
Avg annual Nr of AEL Shutdowns	1	136.0	134.6	61.9	61.9
Avg AEL Shutdown Duration	h	7.6	8.1	9.1	9.4
Avg annual AEL downtime	h	1,034	1,094	562	581
Avg annual Nr of HB Shutdowns	1	34.6	33.7	16.8	16.5
Avg HB Shutdown Duration	h	50.1	50.0	49.1	49.1
Avg annual HB downtime	h	1,732	1,683	826	809

Figure 22 show the curtailment rates for simulated storage combinations. It can be observed, that increasing the combined storage capacity of BESS and H₂ storage reduces the share of unused surplus electricity. The surplus rate in simulations where only BESS is considered appear to reach lower levels, than simulations where only H₂ storage is included. Combinations of high-wind (red and green) show lower overall surplus rates than combinations of low-wind. Low-wind combinations reach lower surplus rates than high wind combinations when only considering BESS for capacities above 3000 MWh. Surplus rates at minimum LCOA configuration range from 18.1–23.8%. The lowest surplus rate at minimum LCOA is achieved for the wind-PV combination of high-wind and low-PV with 18.1%. Of the minimum LCOA configurations the Low-wind low-PV combination yields the highest surplus rate with 23.8%.

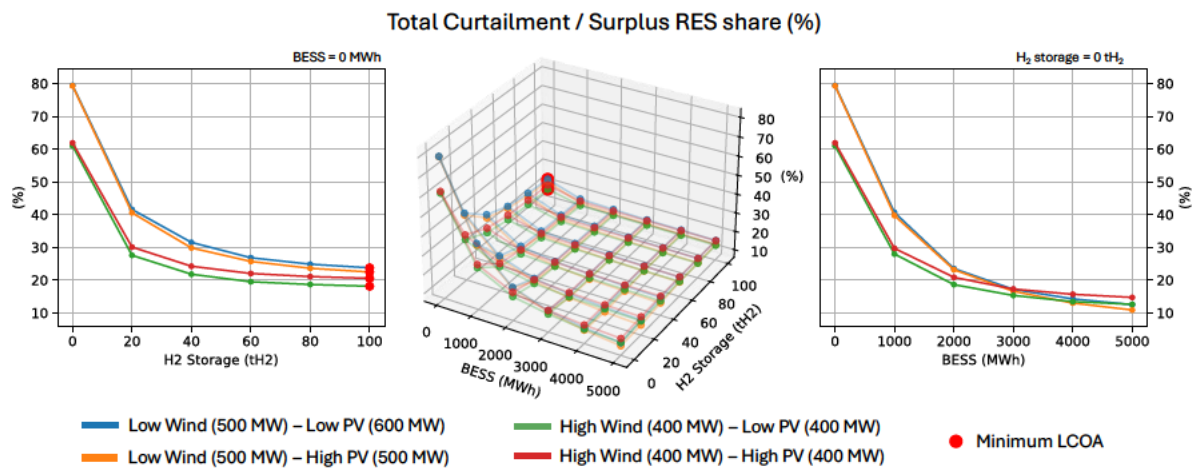


Figure 22: (centre) curtailment rate evaluation for all simulated storage combinations. (left) and (right) show curtailment rate sensitivity to BESS and H₂ storage capacity, respectively.

Figure 23 illustrates that, the inclusion of storage capacities has only a minor influence on the share of grid electricity consumption throughout all simulations. The shares of grid consumption appear to be constant for each combination of wind and PV. When considering no storage capacity at all high-wind combinations (red and green) show a minor drop in grid consumption. The opposite is true for low wind combinations, where the exclusion of BESS and H₂ storage results in a slight increase of grid consumption.

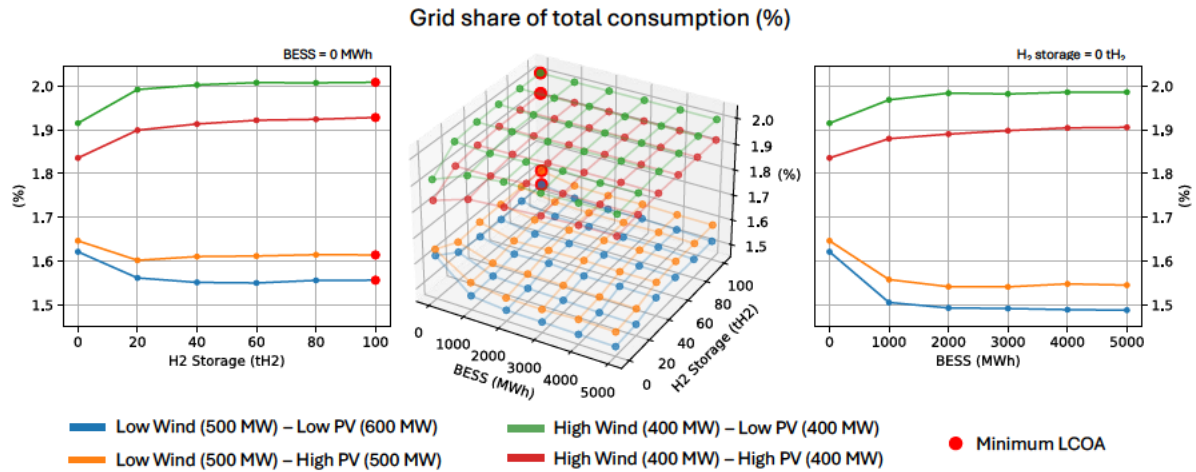


Figure 23: (centre) grid share evaluation for all simulated storage combinations. (left) and (right) show grid share sensitivity to BESS and H₂ storage capacity, respectively

Average annual Ammonia production increases with the addition of storage capacity (see Figure 24). Though the rate of increase reduces the more storage capacity is added. The dynamic appears to show capped growth behaviour, meaning each wind-PV combination closes in on a maximum ammonia production rate. The BESS sensitivity shows that ammonia production is still increasing with additional BESS capacity, suggesting it is farther from the maximum ammonia production rate. In contrast, the H₂ storage sensitivity indicates diminishing returns with increased H₂ storage capacity, implying it is much closer to the system's maximum achievable ammonia production. Generally, plant configurations with BESS systems show higher maximum ammonia production rate ceilings, than configurations with only H₂ storage. At storage configurations that yield minimum LCOAs, the ammonia production rate ranges from 100 to 127 kt of ammonia per year. High-wind combinations (red and green) show 25–27% higher production rates, than low wind combinations.

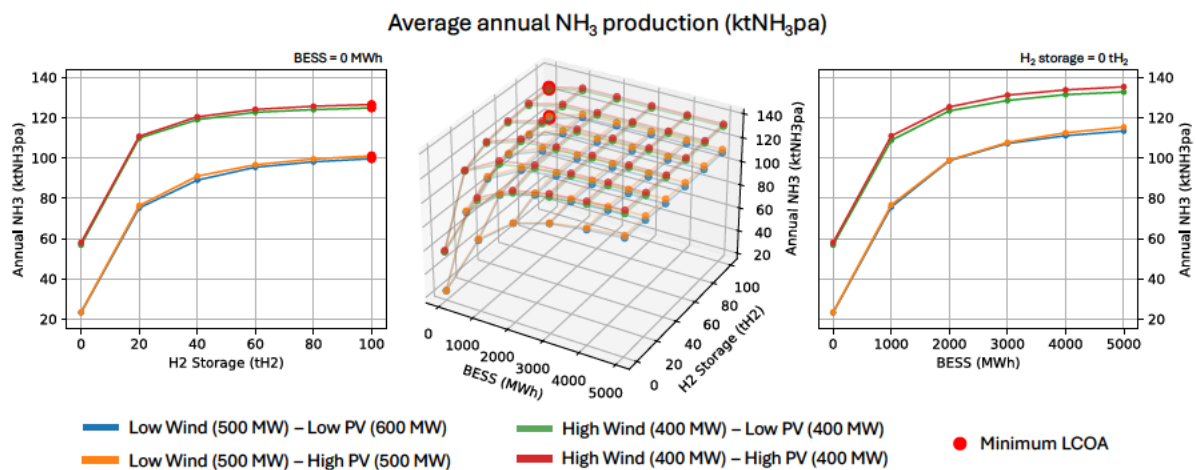


Figure 24: (centre) annual NH₃ production evaluation for all simulated storage combinations. (left) and (right) show annual NH₃ production sensitivity to BESS and H₂ storage capacity, respectively

Utilization of the Haber-Bosch and AEL behaves analogous to the average annual ammonia production (see Figure 25). At minimum LCOA configurations the Haber-Bosch utilization

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ranges from 4,981–6,327 FLH. Low-wind combinations show low utilization rates of 4,981 and 5,053 FLH for low-PV and high-PV combinations, respectively. High-wind combinations show high utilization rates of 6,243 and 6,327 FLH for low-PV and high-PV combinations.

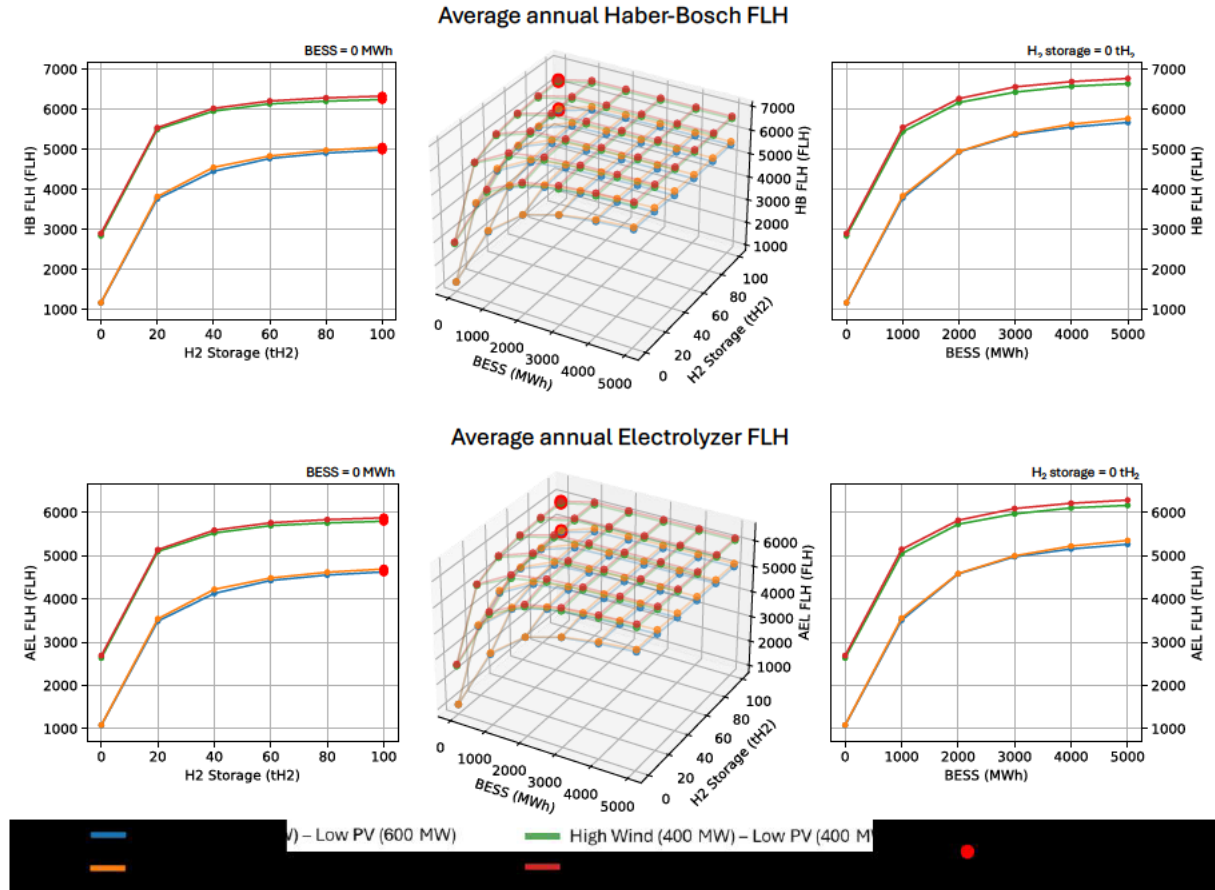


Figure 25: (centre) Average annual utilization evaluation of Haber-Bosch and electrolyzer processing units for all simulated storage combinations. (left) and (right) sensitivity to BESS and H₂ storage capacity, respectively

The evaluation of the annual shut down behaviour of the Haber-Bosch and AEL processing unit shows a decreasing number of shut down instances, the more storage capacity is added (see Figure 26). At minimum LCOA plant configurations, the number of Haber-Bosch shut-downs range from 16.5 to 34.6. As with ammonia production rate, the number of shutdowns appear to close in on a minimum threshold. Especially for H₂ storage capacity the curvature of the sensitivity suggests that the addition of storage capacity beyond 100 t_{H2} would not further reduce the number of shutdown occurrences. For added BESS there appears to be no such minimum threshold. The curvature would rather suggest that, given enough added BESS capacity, 100% uninterrupted Haber-Bosch operation would be technically achievable.

For both Haber-Bosch and AEL the sensitivity on BESS and H₂ storage show a maximum in number of shutdowns for storage capacities of 1000 MWh and 20 t_{H2}, respectively. These maxima are misleading, as they would suggest, that the plant with no storage capacity operates with less interruptions, than configurations with minimal storage. While there are less shutdowns in total, the average duration of each shutdown is longer. For simulations with storage capacities average shutdown durations are between 49.0 and 50.1 hours. This means

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there are rarely instances, where after the restart delay timer is run out, the Haber-Bosch is still unable to start up, and the timer is reset. For simulations where no storage is considered, the average Haber-Bosch shut down durations are around 75 hours for high-wind combinations and 115 hours for low wind combinations. This means, that consecutive shutdowns of the Haber-Bosch processing unit are regularly occurring. This leads to cumulative downtimes of the Haber-Bosch of around 5,500 hours for high-wind combinations and 7,400 hours for low-wind combinations. In the simulations results this shutdown maximum at minimum storage capacities only appears in the sensitivity of low-wind combinations (blue and orange). Though, the same dynamic is true for high-wind combinations (red and green) but is not visible in the results due to the sensitivity resolution of the BESS and H₂ storage.

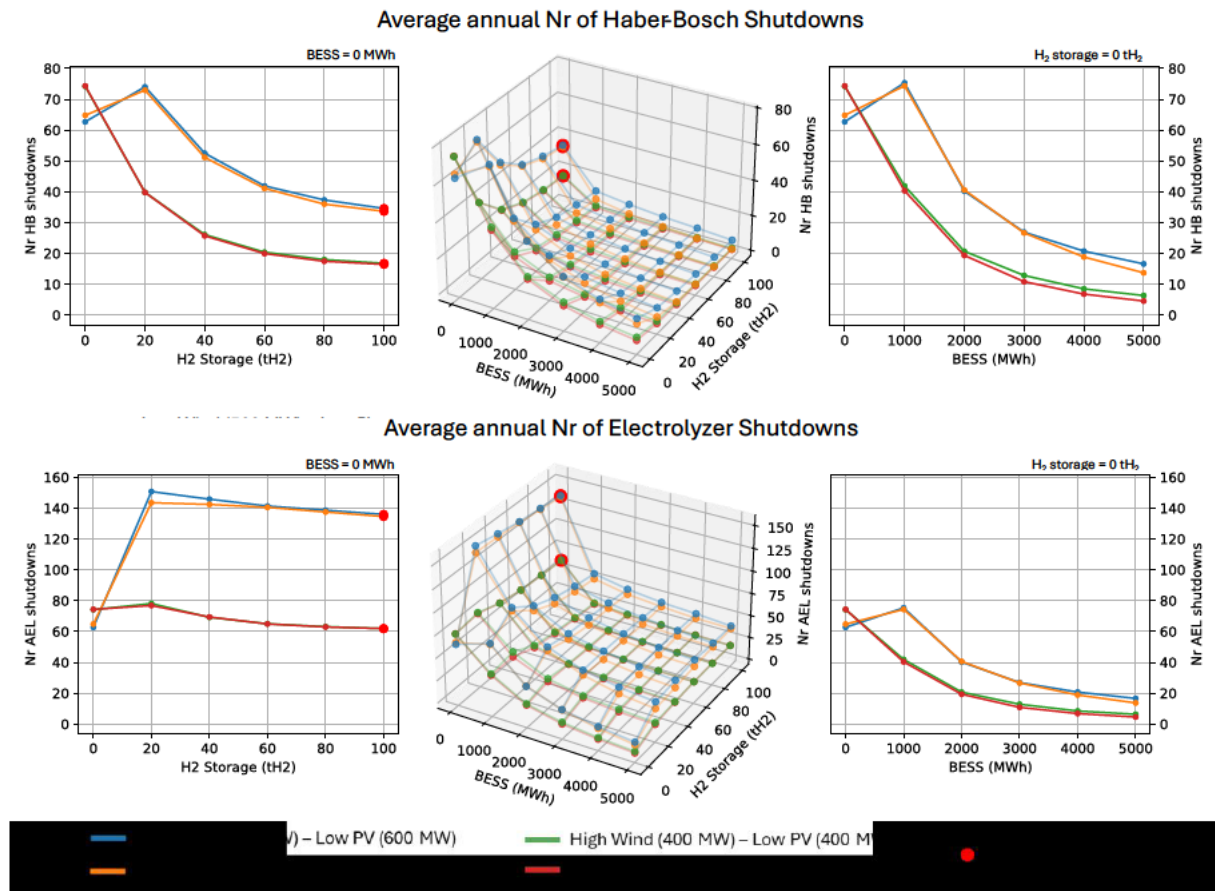


Figure 26: (centre) Average annual shutdown evaluation of Haber-Bosch and electrolyzer processing units for all simulated storage combinations. (left) and (right) sensitivity to BESS and H₂ storage capacity, respectively

7 Discussion

Chapter 7 discusses the key findings of the thesis in relation to the defined research questions. It provides a structured results recap, addresses model limitations, and reflects on their implications for RFNBO-compliant ammonia production.

7.1 Results Recap

The thesis' objective was to evaluate the RFNBO compliant ammonia production under technical, economic, and regulatory constraints. The simulation model developed for this purpose was designed to assess how regulatory compliance can be integrated in a P2A system. This section summarizes the main results derived for each research question.

Research Question 1

The first research question focused on how a simulation model can integrate the operational and regulatory constraints of RFNBO ammonia production.

The resulting model developed in this work incorporates a rule-based dispatch logic, that combines technical and regulatory constraints. Key regulatory elements are implemented directly in the dispatch logic and ensure RFNBO compliant ammonia production. A central feature is the batch-level emissions tracking system, which ensures carbon emissions are allocated and preserved through all modelled processing steps. This is especially important for hydrogen stored in the H_2 storage tank, as emissions must be traced to the final ammonia product. The FIFO tracking logic implemented in the storage tank enables traceability of GHG emissions. The model forms a basis for GHG calculations required for certification under EU voluntary schemes such as ISCC or CertifHy. The result is a regulation-aligned simulation framework capable of evaluating a given P2A system configuration that is operating within REDII DA requirements.

Research Question 2

The second research question focused on the effect of renewable electricity availability on the operation and commercial performance of the P2A system.

This was investigated through a sensitivity analysis of different wind and PV supply configurations. The results confirm that high-yield renewable energy portfolios, particularly those dominated by wind, lead to lower LCOA. In high-yield scenarios, LCOA values as low as 1,521 EUR/t_{NH₃} were achieved. In contrast, low-yield scenarios resulted in values only as low as 1,975 EUR/t_{NH₃}. The relationship between renewable capacity and operational performance was found to be nonlinear. Oversizing renewable capacity beyond a certain point led to increasing LCOA, due to higher curtailment rates while annual ammonia production rates were

stagnating. Wind assets contributed more to operational continuity of the Haber-Bosch and AEL processing units, while PV-heavy portfolios led to more frequent shutdowns. Across all simulated cases, grid electricity usage remained below 2% of total consumption. This highlights the limitations on grid electricity consumption that are implemented in the model to ensure RFNBO compliance of the produced ammonia.

Research Question 3

The third research question concentrated on the impact of storage integration on the operation and commercial performance of the P2A process.

For the simulated P2A systems, the results show that integrating large H₂ storage capacities enhances commercial performance, with LCOA continuously decreasing as storage capacity increases. In contrast, BESS integration initially reduces LCOA at small BESS capacities, but this trend reverses beyond a certain point. At higher capacities, the increasing capital and degradation-related replacement costs of BESS begin to outweigh their operational benefits, resulting in higher LCOA. At the same time, BESS demonstrates superior operational performance in comparison to H₂ storage. P2A configurations with high BESS capacities show higher annual ammonia production rates, reduced unused surplus electricity, and overall fewer shutdowns of AEL and Haber-Bosch synthesis loop. While BESS enhances flexibility and process stability, its high costs reduce its economic viability at larger capacities. While less dynamic, H₂ storage offers a more cost-effective means of ensuring compliance and maintaining production continuity under REDII constraints.

7.2 Limitations of the Model

In general, there are many challenges associated with modelling energy systems. A fundamental limitation is the need to simplify complex systems to implement them mathematically to the desired depth, and simplifications are essential for this (Razzhivin et al., 2023). The following section outlines the relevant limitations of the simulation model developed in this thesis, grouped into three thematic categories: technical process modelling, market and economic assumptions, and regulatory and system scope limitations.

Technical Process Modelling Simplifications

Several limitations arise from simplifications in the representation of the core P2A units. The electrolyzer efficiency is assumed constant for the entire operational load range, neglecting the known variability in efficiency depicted in Figure 1. This may result in over- or underestimation of hydrogen production, especially under fluctuating renewable supply (Ikäheimo et al., 2018). Similarly, the specific energy and hydrogen demand of the Haber-Bosch synthesis unit are treated as fixed values, independent of variable load operation. Real-world deviations due to ramping, off-spec operation, or startup energy consumption are therefore not captured (Yu et al., 2024). Additionally, the model assumes no ramp-restrictions for the Haber-Bosch synthesis loop, ignoring the thermal inertia and mechanical constraints typically present in high-pressure systems (Verleysen et al., 2023b). The representation of storage utilization is also simplified, as storage is only used to maintain minimum load operation. Strategies to maximize

ammonia yield during part-load operation are not implemented, to reduce computational demands. Lastly, BESS degradation is modelled in a simplified calendar aging approach, rather than utilization-dependent cycle-based degradation, which may misrepresent capacity levels and subsequent replacement needs (Gräf et al., 2022).

Market and Economic Assumptions

The model makes several simplifications in its treatment of market interactions and economic parameters. Additional electricity, beyond PPA volumes, is modelled as being purchased on the spot market at a fixed price. Conversely, unused surplus electricity from the PPA is sold on the spot market at a lower fixed price. This implementation disregards the volatility and extreme values seen in real-world spot markets (see Figure 8). While this simplified approach limits realism, it deliberately avoids introducing a false sense of precision. Future electricity market dynamics are uncertain. This is especially true as grids become increasingly dominated by fluctuating renewable generation. Therefore, any forward-looking modelling based on historical spot price profiles should be interpreted with caution. Similarly, current regulatory provisions that allow grid electricity use during imbalance settlement periods for RFNBO production (DA 1184, Art. 4(3)) are not included. The required data from TSOs, to prove compliance, is currently not publicly available. Predictions on an hourly basis are therefore not feasible. Furthermore, the model does not account for economies of scale. Specific CapEx are assumed constant across all process unit sizes, which may overstate cost for larger installations where specific CapEx would be expected to decrease. Finally, revenues from byproduct sales are not considered in the model (i.e. oxygen, surplus hydrogen, low and high temperature usable waste heat). While additional revenues from byproduct sales could offer meaningful LCOA reductions (Campion et al., 2023), they are dependent on the project-specific context and should not be considered in a base case simulation.

Regulatory and System Scope Limitations

The model adopts a conservative compliance approach, assuming that 100% of ammonia production must meet RFNBO criteria. While this reflects the thesis' focus on RFNBO compliant mandate-driven markets, it excludes more flexible operational strategies. One such strategy would be the incorporation of non-compliant ammonia production from grid electricity during periods of renewable scarcity or extremely low spot market prices. This approach could not only result in increased plant utilization rates and ammonia yields, but introduce an additional mechanism of shutdown mitigation, apart from onsite storage capacities. By modelling only fully compliant operation, the simulation model neglects these alternative strategies and therefore limits the operational flexibility that economic operators may realistically pursue. Furthermore, the model does not account for regulatory relaxations that apply once the grid surpasses 90% renewable electricity penetration within the simulated project lifetime. Consequently, the model may overstate the need for strict hourly matching, additionality, and local renewable sourcing, required under sub 90% RES-share grid conditions. Additionally, the system boundary is limited to the ex-works level, excluding emissions from downstream processes such as ammonia transport, distribution, and potential cracking for hydrogen recovery. While this aligns

with RFNBO certification boundaries, it neglects emissions and energy consumption relevant to a complete well-to-wake assessment.

7.3 Interpretation and Implications

Minimum LCOAs obtained from the sensitivity analyses on renewable electricity availability (chapter 6.1) and storage configuration (chapter 6.2) range from 1,521 to 1,975 EUR/ t_{NH_3} . In comparison, conventional fossil-based ammonia is currently priced at approximately 550 EUR/ t_{NH_3} (James Burgess, 2025), highlighting the substantial cost gap. Therefore, electrolysis-based ammonia via the P2A pathway in Germany is far from being competitive on the open commodity market. The simulation results underscore that RFNBO compliance is a prerequisite for commercial viability of P2A projects. Only RFNBO-certified ammonia is eligible for access to mandate-driven markets established under RED targets (Appendix A.3). In these markets, obligated parties are willing to pay premium prices, as non-compliance would result in penalties that are expected to be even more costly (i.e. FuelEU Maritime penalty system). In contrast, P2A ammonia that does not meet RFNBO criteria would be forced to compete with fossil ammonia, without the benefit of policy related pricing premiums. For reference, based on German grid prices of 60 to 80 EUR/MWh and a specific consumption of around 11 MWh/ t_{NH_3} , electricity cost alone would reach 660 to 880 EUR/ t_{NH_3} , already surpassing fossil ammonia prices.

In their review of green ammonia production pathways Ojelade et al (2023) report cost for P2A ammonia ranging from 350 to 1,900 EUR/ t_{NH_3} . Electricity costs are attributed as the main cost driver. In their location specific optimization of a 68 t_{NH_3}/h P2A plant, Campion et al (2023) narrow this range down to 760 to 1070 EUR/ t_{NH_3} for high RES locations in northern Chile (PV), Denmark (Wind) and southern Australia (Wind + PV). This aligns with the results derived from the sensitivity analysis on renewable availability. They show that ammonia production cost increase with lower yield RES assets. Main driver for lower ammonia production cost, was the selection of the supplying wind asset. The specific electricity price for high yield RES assets is lower than low yield assets, due to PPA price assumptions being based on EEG tender results and the reference yield model under EEG §36h. At the same time do high yield wind assets results in higher annual ammonia production rates, which in turn reduces the relative cost contribution of capital expenditures. These findings highlight that renewable resource quality and structure are central design parameters of a P2A system. Project developers should prioritize sites with high FLH and favourable generation profiles. Additionally, they must assess not only average yield but the alignment between generation and process load. The simulation model provides a means to quantify these interactions and inform RES capacity decisions early in project development.

While the results on storage integration determined that H_2 storage yields lower overall ammonia production costs, the superior operational performance of BESS should not be neglected. Especially the reduction in Haber-Bosch shutdown occurrences resulting from BESS integration is essential for avoiding prolonged production downtime from cumulating restart delays. Additionally, the technical necessity of continuous Haber-Bosch operation is discussed at length in the literature, citing risks such as accelerated thermal fatigue in reactor materials, compromised catalyst stability, and increased risk of mechanical failure (Narciso et al., 2025;

Yu et al., 2024). Although the BESS' standalone economic appeal is constrained especially at larger capacities, its ability to maintain Haber-Bosch operation make it an effective complement to H₂ storage. A hybrid storage system may offer a more robust system configuration at the cost of increased LCOA. However, the current model restricts storage use to maintaining minimum load operation, without allowing storage to support partial-load maximization. This limitation may underestimate the full potential of both storage technologies. Future model developments should address this by enabling a more flexible dispatch logic that can capture additional operational benefits of storage integration. This would allow for a more accurate assessment of system performance and more informed storage sizing decisions.

Unlike MILP-based optimization models, that primarily focus on cost minimization, the simulation model developed in this thesis is designed to evaluate how a given P2A system configuration performs under strict implementation of RFNBO requirements. It supports batch-level GHG tracking and enables emissions transparency in alignment with EU voluntary certification schemes. While the model does not generate economically optimal system designs, it offers a compliance-centred perspective that could complement cost-optimization approaches. In their optimization of a P2A plant, Campion et al. (2023) apply grid emission intensities ex post and highlight the risk of underestimating ammonia emission intensities, subsequently recommending real-time emissions allocation. Similarly, Wang et al. (2022), in their comparison of grid-connected and islanded P2A systems, call for embedded emissions tracking within the optimization process. Combining rule-based emissions accounting with MILP or other optimization techniques represents a promising direction and should be considered in future research. Such a hybrid approach could merge the benefits of optimization for investment planning with the traceability needed for RFNBO compliance.

8 Conclusion

This section begins with a summary of the thesis, followed by an outlook on potential improvements to the simulation model and directions for future research, ultimately concluding the work.

8.1 Summary

This thesis investigates the feasibility of producing ammonia as a renewable fuel of non-biological origin (RFNBO) in accordance with the EU Renewable Energy Directive (RED II), specifically addressing the requirements of Delegated Regulations (EU) 2023/1184 and 2023/1185. These regulations impose strict conditions on temporal correlation between electricity consumption and renewable generation, as well as a GHG emission threshold of 28.2 gCO₂eq/MJ fuel. The core objective of the work was to develop a computational framework that enables a techno-economic assessment of ammonia production systems under these regulatory constraints. Specific focus was on the challenges associated with continuous operation of the inherently inflexible Haber-Bosch synthesis process under supply of fluctuating renewable electricity sources.

The model was developed in three steps. Firstly, the regulatory landscape for renewable hydrogen-derived fuels was systematically reviewed in chapter 3. The key requirements were translated into quantifiable constraints that could be implemented in a simulation model. Secondly, the techno-economic system boundary was defined in chapter 4. The modelled ammonia production system includes renewable electricity imports via PPAs, grid electricity imports from the spot market, a battery energy storage system, a water electrolyzer, a hydrogen compressor and storage tank, and the Haber-Bosch synthesis loop with integrated air separation unit. The techno-economic parameters required for the simulation model were presented and discussed. Current values were taken from scientific literature, official reports from energy associations, or calculated and subsequently adopted. The third and last step involved the design, implementation, and testing of a Python-based simulation tool of the Power-to-Ammonia (P2A) process, based on the derived techno-economic and regulatory model requirements. The developed model imposes a rule-based dispatch logic to generate conclusive hourly mass and energy balances for each component of a given P2A system configuration over the simulated project duration. At each step, the tool ensures that the electricity consumed in the electrolyzer can be considered renewable under the hourly correlation requirement and the cumulative emissions intensity of the produced ammonia remains within the GHG threshold. Post-simulation, performance indicators such as Haber-Bosch utilization, surplus electricity rates, ammonia output, and LCOA are determined.

To assess the P2A system's operational performance and sensitivity to design decisions, a range of simulations were performed varying the installed capacities of renewable generators

and storage units. The results showed that high-yield renewable energy sources, especially wind, significantly reduce LCOA due to lower specific electricity prices and higher annual output, which dilute CapEx. These findings confirm the importance of selecting locations with favourable generation profiles and high full-load hours. While H₂ storage proved most effective in lowering ammonia production costs, battery storage contributed operationally by reducing Haber-Bosch shutdowns. Although battery systems are less attractive economically, their positive impact on Haber-Bosch process stability positions them as a valuable complement to H₂ storage. Importantly, due to computational complexity, the model restricts storage dispatch to minimum load maintenance, potentially underestimating the benefits of hybrid storage systems.

In conclusion, this thesis demonstrates that the developed model is suitable to assess techno-economic feasibility of RFNBO-compliant ammonia production from fluctuating renewable electricity sources. The model provides a transparent and policy-aligned perspective to assess ammonia systems at an hourly resolution, bridging the gap between regulatory compliance and techno-economic optimization. The thesis contributes to the ongoing modelling efforts in recent research to discuss the deployment of renewable hydrogen and ammonia in hard-to-abate sectors.

8.2 Outlook

To give an outlook, further development options of the simulation framework are presented. A key improvement would be the expansion of the rule-based dispatch logic to a more dynamic approach, such as model predictive control, which could enable optimized storage utilization beyond mere minimum load maintenance. This would allow the system to anticipate and respond to fluctuations in renewable supply and process demand. Additionally, the integration of non-linear efficiency characteristics for both the electrolyzer and the Haber-Bosch synthesis loop would allow for a more accurate representation of part-load behaviour and ramping dynamics. This would improve the precision of mass and energy balance calculations under variable operating conditions. Another conceivable extension would be to incorporate economies of scale into the techno-economic parameters. The current model assumes constant specific investment costs, potentially overestimating costs for larger-scale P2A configurations. Finally, applying the model to a specific industrial use case and expanding the system boundary to include downstream energy use and emissions would enable a full well-to-wake assessment. This includes processes such as ammonia transport, cracking for hydrogen recovery, and end-use in sectors like steelmaking. This would provide deeper insights into the overall climate impact and system integration potential of RFNBO ammonia across its entire value chain.

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Statutory Declaration

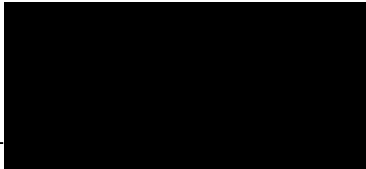
Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Hiermit versichere ich, dass ich die vorliegende Arbeit ohne fremde Hilfe selbständig verfasst und nur die angegebenen Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

Statutory Declaration

I hereby declare that I have written this thesis independently without external help and that I have only used the sources indicated. Passages taken verbatim or in the same sense of other works are marked with an indication of the sources.

Hamburg, 12.05.2025



Maximilian Riedl

Appendix

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A. EU Policy

A.1 EU Emissions Trading System

The EU Emissions Trading System (EU ETS), together with the Carbon Border Adjustment Mechanism (CBAM), is the EU's main instrument for reducing GHG emissions. It applies to all EU Member States, as well as the European Economic Area (EEA), meaning Iceland, Liechtenstein and Norway. In its current state EU ETS covers energy-intensive industries, power plants and aviation, thereby covering slightly less than 40% of the EU's CO₂ emissions (Clean Hydrogen JU, 2025). With the revision in 2023 as part of the Fit for 55 package, the maritime sector has been included in the scheme. In addition, a separate emissions trading system for buildings and road transport (ETS2) has been introduced, with monitoring and reporting starting in 2025 and full implementation scheduled for 2027 (European Commission, n.d.; European Union, 2023d).

The EU ETS operates on a cap-and-trade principle, ensuring a defined environmental outcome by placing a limit on total carbon emissions from covered sectors. The number of emission allowances issued serves as the quantitative cap, with these allowances either auctioned or allocated for free to companies. Businesses must regularly surrender allowances equivalent to their actual emissions and they can trade allowances as needed ("Delivering a Climate Neutral Europe," 2024, p. 59). Over time, the total number of allowances is gradually reduced at a predictable rate, following a linear reduction factor (LRF) to drive sustained emissions reductions. Under ETS1, emissions are targeted for a 62% reduction by 2030 (compared to 2005 levels), with an LRF of 4.3–4.4%, while ETS2 aims for a 42% reduction by 2030, applying an initial LRF of 5.1% until 2027 (Clean Hydrogen JU, 2025).

For EU ETS to function effectively, market confidence in compliance is essential. The system therefore relies on robust monitoring, reporting and verification procedures to ensure transparency and accountability. Non-compliance results in a penalty of €100 per tonne of excess emissions, adjusted for inflation, in addition to the obligation to compensate for the shortfall. Historically, compliance rates have been high, with over 99% of operators in stationary installations and aviation meeting their obligations on time ("Delivering a Climate Neutral Europe," 2024, p. 61).

Economists generally advocate for full auctioning of emission allowances, in line with the polluter-pays principle, which is explicitly referenced in the EU treaty. However, implementing this approach unilaterally could undermine the competitiveness of European industries, particularly if other major economies do not impose comparable carbon pricing or adopt similarly stringent emission reduction measures. While emissions trading provides a clear and transparent price signal, policymakers must carefully balance climate ambitions with the risk of industrial relocation to regions with less stringent environmental regulations. The associated increase of emissions from relocation is commonly referred to as carbon leakage. There are two primary ways to address the risks of competitiveness loss and carbon leakage ("Delivering a Climate Neutral Europe," 2024, p. 83):

- Internal Adjustments: The EU has traditionally mitigated these effects by granting free allowances to industries exposed to global competition, helping to offset the financial burden of carbon pricing and prevent production shifts.

- **External Adjustments:** As an alternative, the EU can impose a carbon cost on imported goods from countries that do not apply equivalent emissions regulations. This approach has been formalized under the EU Green Deal through the introduction of the Carbon Border Adjustment Mechanism, which applies to a select group of carbon-intensive products.

By implementing CBAM, the EU aims to level the playing field for domestic industries while ensuring that global emission reductions remain effective, rather than shifting carbon-intensive activities outside Europe's regulatory framework.

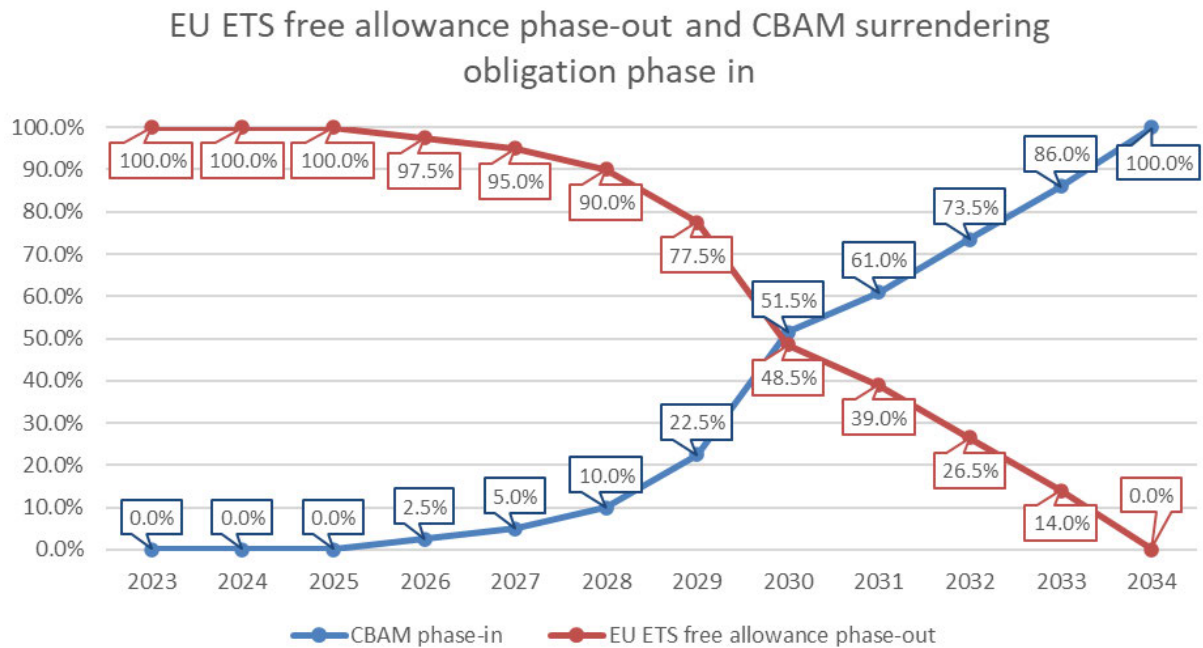
A.2 Carbon Border Adjustment Mechanism

CBAM is a charge on imported goods. CBAM is designed to replicate the carbon pricing instrument of the EU ETS. In its initial form, CBAM will cover relevant energy-intensive products, namely, iron and steel, cement, aluminium, fertilisers, hydrogen, and electricity (Graichen et al., 2023).

CBAM begins with a transitional period (2023–2025), during which importers must monitor and report emissions, but are not required to verify data or surrender CBAM certificates. From 2026 onward, importers must purchase and surrender CBAM certificates to offset embedded emissions, with obligations gradually increasing until full implementation in 2034. This would create a stronger incentive to decarbonise industrial processes. Thus, the role of renewable hydrogen is expected to increase, especially in sectors with few other alternatives, such as in steel and fertilisers production (Clean Hydrogen JU, 2025).

The CBAM certificates to be surrendered shall be adjusted to reflect the extent to which EU ETS allowances are allocated free of charge under EU ETS. Phase in of CBAM is mirrored with the phase out of ETS free allowances, as depicted in the figure below (European Union, 2023d). This is in part done to harmonize with the principle of free trade and specifically the General Agreement on Tariffs and Trade (GATT) under the World trade organisation (WTO) and to not constitute a protectionist market distorting import tariff as has been argued by trade partners such as China, Brazil and India (Mag. Dr. Wolfgang Sailer, 2024; Mehling et al., 2019).

Once CBAM is fully phased in, certificate costs for imported ammonia could therefore amount to $210 \text{ EUR} / t_{\text{NH}_3}$ based on $1.7 t_{\text{CO}_2}$ direct emissions per t_{NH_3} and a projected EU ETS certificate price of $120 \text{ EUR} / t_{\text{CO}_2}$ (Graichen et al., 2023).



A.3 RED Targets

REDII and REDIII 2030 targets for overall energy consumption, transport sector, industry and fuel specific targets. Table adapted from (NOW GmbH, 2024)

<i>Targets 2030</i>	<i>Targets in RED II (2018)</i>	<i>Targets in RED III (2023)</i>
EU targets		
Renewable energy in the EU	Min. 29% share of renewable energy in final consumption of the EU	At least 42.5% share of renewable energy in final consumption of the EU, with a further indicative target of 2.5%.
Industry targets		
Renewable energy in industry	NA	At least 1.6% increase in use of renewable energy in industry per year from 2021 to 2025 and from 2026 to 2030.
RFNBOs	NA	At least 42% of hydrogen used for energy and non-energy purposes in the industry comes RFNBOs by 2030. At least 60% by 2035. RFNBO share in industrial use can be reduced by 20% if the national contribution to the overall binding EU target is met and the share of hydrogen from fossil fuels is no higher than 23% in 2030 and 20% in 2035.
Transport targets		

Targets 2030	Targets in RED II (2018)	Targets in RED III (2023)
Renewable energy in transport	At least 14% share of renewable energy in final consumption of road and rail transport	At least 29% share of renewable energy in final consumption of all energy used in transport. Or a minimum of 14.5% reduction in GHG compared to emissions that would have been created by fossil fuel use instead.
Advanced biofuels (feedstocks listed in Annex IX, part A)	3.5% share of advanced biofuels in final consumption of road and rail transport x2 multiplier	5.5% share of advanced biofuels and RFNBOs in final consumption of all energy supplied to transport, with a 1% RFNBO minimum share Indicative goal of at least 1.2% of energy used in maritime transport to come from RFNBOs in 2030 x2 multiplier for advanced biofuels and RFNBOs
RFNBOs	No sub-target Additional multipliers in aviation and maritime transport: x1.2	Additional multipliers in aviation and maritime transport: x1.2 for advanced biofuels and x1.5 for RFNBOs

A.4 Multipliers

As a directive, the prescribed targets must be implemented into national law. The methods for achieving these targets are not explicitly defined and are subject to each member state's indicative target pathway. The assessment criteria in the National Renewable Energy Action Plans (NREAP) are used to evaluate the implementation measures (Zygierewicz and Sanz, 2021).

Suggested implementation measures to fulfil imposed targets on the transport sector include the application of fuel specific multipliers on the energy content of fuels used in transport. These multipliers aim to promote innovative fuel technologies, supporting the introduction of future alternative fuels. On the one hand, multipliers on the energy content of a specific fuel are drivers for the introduction of innovative fuels, as their weight in target fulfilment is increased. On the other hand, multipliers effectively reduce the actual quantities of fuel required to meet the energy content based minimum fuel quota, as less fuel is required to meet the prescribed quota (European Union, 2023a, 2018; NOW GmbH, 2024).

This effect becomes evident when looking at the transport sector targets set out in REDIII (see Appendix A.3). The overall sector target is 29 % renewable energy consumption. The combined fuel specific minimum quota is 5.5 % RFNBO and advanced biofuel (aBioF) in final consumption of all energy supplied to transport, with a minimum share of 1 % RFNBO. With the multiplier of 2 on both RFNBO and aBioF, the mandated 5.5 % and 1 % fuel quota translate to 2.75 % and 0.5 % energy supply targets respectively. When consumed in maritime or aviation transport, additional stacking multipliers of 1.5 for RFNBO and 1.2 for aBioF may be applied, resulting in a combined multiplier of 3 for RFNBO and 2.4 for aBioF. The indicative 1.2 % minimum quota for RFNBO used in the maritime transport translates to a 0.4 % energy supply

target. An overview of EU and sector specific renewable consumption targets, as well as fuel specific minimum quotas and multipliers relevant to RFNBO, is given in Appendix A.3.

A.5 REDII Implementation Germany (37th BImSchV)

In Germany, the transposition of REDII into national law placed the obligation to meet the transport sector targets on fuel suppliers. According to the thirty-seventh ordinance on the Implementation of the federal emission control act (37th BImSchV), electricity-based fuels as defined in the DAS, can contribute to the GHG quota regulation (THG Quoten Regelung) in §37a of the federal emission control act (BImSchG), which fuel suppliers are obliged to meet (BImSchG, 2025; BImSchV, 2024). Therefore, fuel suppliers can comply with regulations by incorporating sustainable fuels (RFNBO, aBioF, etc) or participating in GHG emissions trading to meet the GHG quota and avoid penalties, similar to EU ETS.

This means that the general eligibility of RFNBOs for quota reduction and the incentives to use RFNBOs through a multiplier of 3 on the amount of energy used, have so far been implemented. However, the new minimum quotas for 5.5 % aBioF & RFNBO and at least 1.0 % RFNBO added in RED3 have not yet been transposed into national law and are still pending in Germany.

B. RES Asset Overview

B.1 Input Renewables.Ninja

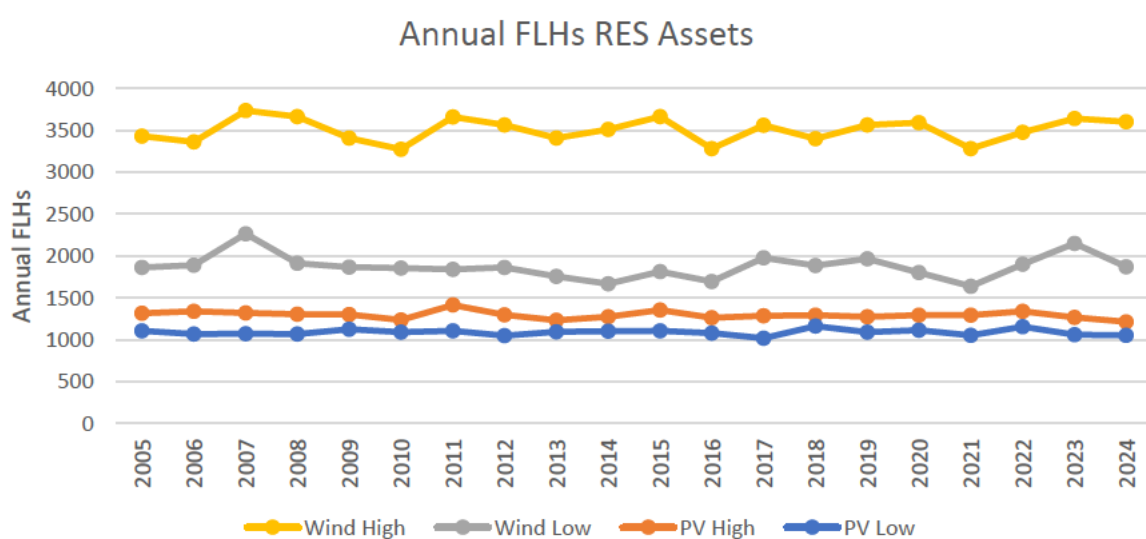
The following table summarizes the Renewables.Ninja inputs to generate the 20-year RE time series used in this thesis:

	<i>Wind High</i>	<i>Wind Low</i>	<i>PV High</i>	<i>PV Low</i>
Date range	01.01.2005 – 31.12.2024			
Dataset	Merra2			
Latitude	53.90	48.65	47.86	53.30
Longitude	10.10	13.03	10.79	9.30
Capacity (kW)	1			
Turbine	Vestas V162 5600	Vestas V117 3600	–	–
Height (m)	110	120	–	–
System loss	–	–	0.1	0.1
Tracking	–	–	No	No
Tilt angle (°)	–	–	38	38
Azimuth (°)	–	–	180	180

B.2 Summary annual FLH

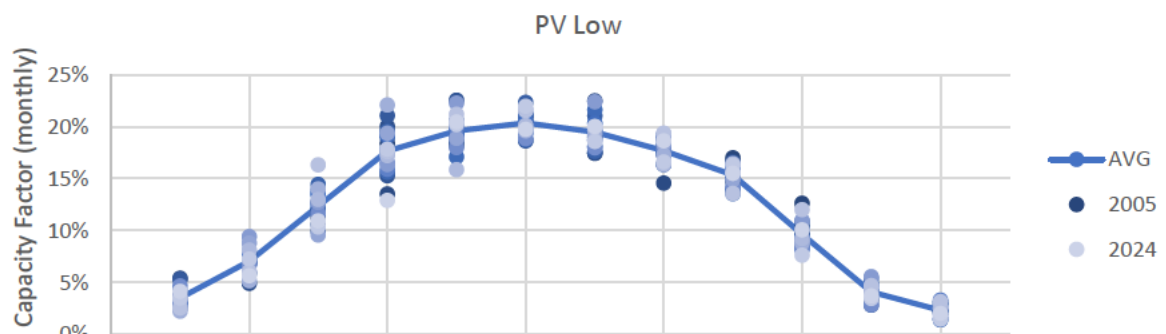
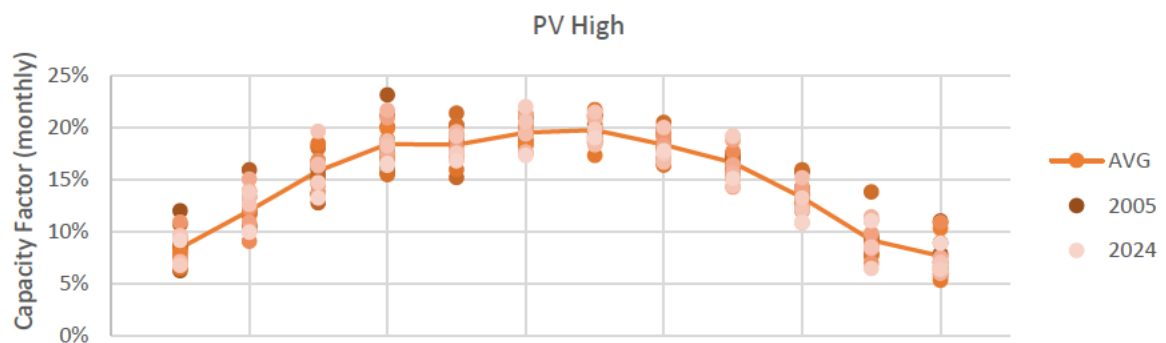
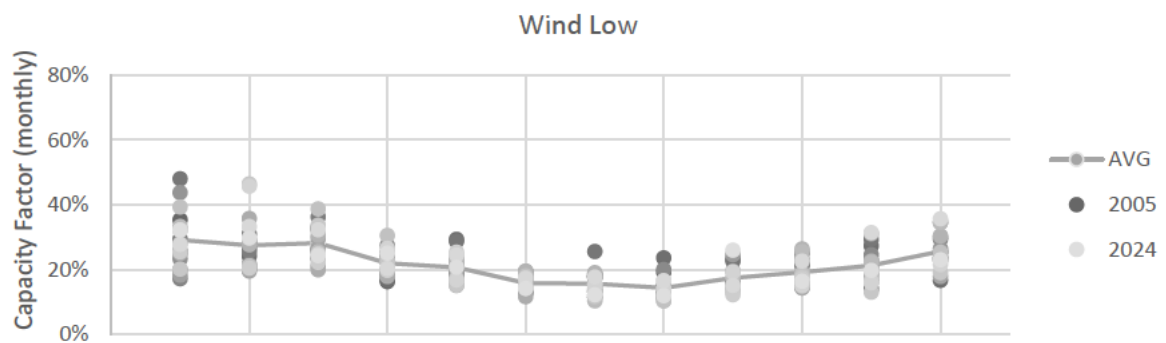
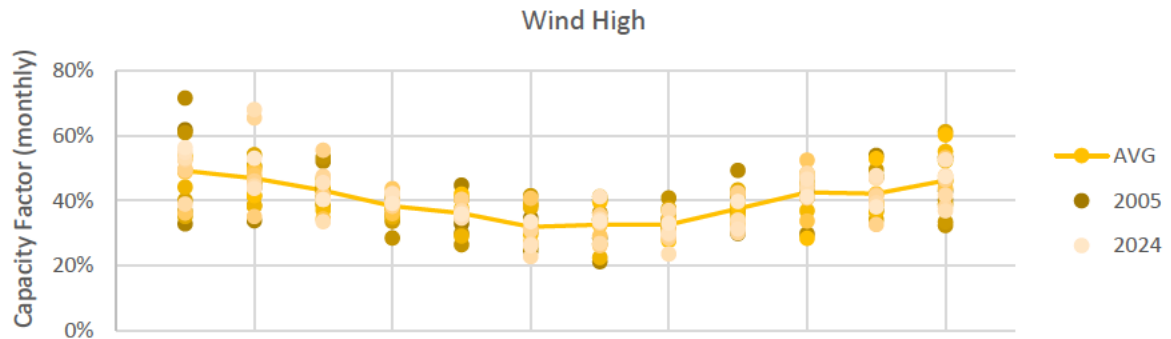
The table and figure below show the annual full load hours for each asset over the 20-year period.

Year	Wind High	Wind Low	PV High	PV Low
2005	3431	1864	1318	1105
2006	3362	1889	1339	1069
2007	3736	2266	1320	1072
2008	3663	1914	1305	1070
2009	3407	1867	1302	1125
2010	3274	1855	1238	1093
2011	3659	1842	1415	1105
2012	3564	1862	1299	1049
2013	3409	1758	1233	1097
2014	3511	1669	1275	1103
2015	3662	1815	1356	1108
2016	3281	1696	1265	1080
2017	3562	1978	1286	1019
2018	3399	1888	1294	1163
2019	3565	1967	1275	1090
2020	3592	1802	1295	1116
2021	3280	1639	1295	1052
2022	3475	1901	1340	1157
2023	3641	2150	1269	1061
2024	3602	1870	1215	1055



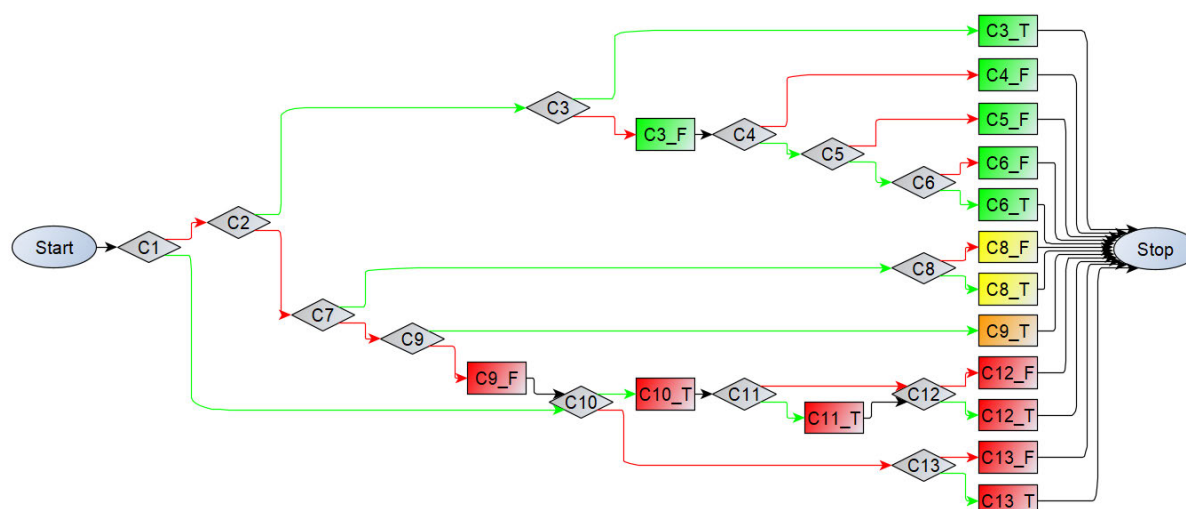
B.3 Seasonal Variability

The figures below illustrate how the monthly average capacity factors vary from January to December over the 20-year period for each RES asset.



XXX

C. Detailed Description of the Rule-Based Dispatch Logic



Step	Type	Description
C1	Condition	Is the Haber-Bosch synthesis restricted from operating under the re-start delay timer?
C2	Condition	Is there more el. energy from RES, than necessary to supply and operate the Haber-Bosch synthesis at nominal load? $C2: E_{RES,t} \geq E_{plant,t}^{nom}$
C3	Condition	Are BESS and/or H ₂ storage below minimum required storage level? $C3: SOC_{St,t} < SOC_{St,min} \vee SOC_{BESS,t} < SOC_{BESS,min}$
C3_T	Action	Determine plant operation. If after each step there is remaining el. energy from RES, continue with the next. Any leftover el. energy will be Surplus. 1. Operate Syn at min load with direct H₂-Feed from ELY 2. Charge BESS to $SOC_{BESS,min}$ 3. Charge H₂ storage to $SOC_{St,min}$ 4. Operate Haber-Bosch synthesis at maximum possible load 5. Max charge BESS 6. Max charge H₂ storage
C3_F	Action	Set Haber-Bosch to nominal operational load with direct H ₂ -feed from AEL. Determine remaining el. energy: $E_{RES,remain,t} = E_{RES,t} - E_{plant,t}^{nom}$
C4	Condition	Is there empty storage capacity in H ₂ storage? $C4: SOC_{St,t} < 100\%$

Step	Type	Description
C4_F	Action	Use $E_{\text{RES,remain},t}$ to charge BESS as much as possible, minding maximum storage capacity $E_{\text{BESS,cap},t}$ and rated power $P_{\text{BESS,nom}}$. Leftover el. energy will be surplus $E_{\text{surplus},t}$
C5	Condition	Would there be el. energy remaining after max charging H₂ storage with the compressor running on maximum possible grid electricity share? $\text{C5: } E_{\text{RES,remain},t} > m_{\text{H}_2,\text{El} \rightarrow \text{Co},t} \cdot \text{SEC}_{\text{El},t} + E_{\text{Co},t}$ with: $E_{\text{Co},t} = m_{\text{H}_2,\text{El} \rightarrow \text{Co},t} \cdot \text{SEC}_{\text{Co}} = E_{\text{Co,RES},t} + E_{\text{Co,grid},t}$
C5_F	Action	Use $E_{\text{RES,remain},t}$ to charge H ₂ storage as much as possible. Include maximum permissible share of grid electricity in the compressor consumption $E_{\text{Co,grid},t}$ so that $CI_{\text{H}_2,\text{Co} \rightarrow \text{St},t} \leq CI_{\text{H}_2,\text{Co} \rightarrow \text{St},\text{max}}$
C6	Condition	Would there be el. energy remaining after max charging H₂ storage and max charging BESS, with the compressor running on maximum possible grid electricity share? $\text{C6: } E_{\text{RES,remain},t} > m_{\text{H}_2,\text{El} \rightarrow \text{Co},t} \cdot \text{SEC}_{\text{El},t} + E_{\text{Co},t} + E_{\text{BESS,in},t}$ with: $E_{\text{Co},t} = m_{\text{H}_2,\text{El} \rightarrow \text{Co},t} \cdot \text{SEC}_{\text{Co}} = E_{\text{Co,RES},t} + E_{\text{Co,grid},t}$
C6_T	Action	Use $E_{\text{RES,remain},t}$ to charge H ₂ storage and BESS as much as possible. Include minimum required share of grid electricity in the compressor consumption $E_{\text{Co,grid},t}$ so that $CI_{\text{H}_2,\text{Co} \rightarrow \text{St},t} \leq CI_{\text{H}_2,\text{Co} \rightarrow \text{St},\text{max}}$
C6_F	Action	Use $E_{\text{RES,remain},t}$ to charge H ₂ storage and BESS as much as possible. Include maximum permissible share of grid electricity in the compressor consumption $E_{\text{Co,grid},t}$ so that $CI_{\text{H}_2,\text{Co} \rightarrow \text{St},t} \leq CI_{\text{H}_2,\text{Co} \rightarrow \text{St},\text{max}}$
C7	Condition	Is there enough el. energy from RES together with its corresponding maximum possible share of grid electricity, to operate the Haber-Bosch synthesis at or above minimum load? $\text{C7: } \frac{E_{\text{RES},t}}{1 - \gamma_{\text{max}}} \geq E_{\text{plant},t}^{\text{min}} = \lambda_{\text{Syn,min}} \cdot E_{\text{plant},t}^{\text{nom}}$
C8	Condition	Are BESS and/or H₂ storage at or above the required minimum storage level? $\text{C8: } SOC_{\text{St},t} \geq SOC_{\text{St,min}} \vee SOC_{\text{BESS},t} \geq SOC_{\text{BESS,min}}$
C8_T	Action	Set part load operating point of Haber-Bosch synthesis according to a available $E_{\text{RES},t}$ with maximum grid integration.

Step	Type	Description
C8_F	Action	Operate Haber-Bosch at minimum load with direct H₂ feed from AEL. Determine remaining el. energy from RES $E_{\text{RES,remain},t}$ and iterate through the following steps until $E_{\text{RES,remain},t} = 0$ 1. Charge BESS to $\text{SOC}_{\text{BESS,min}}$ 2. Charge H₂ storage to $\text{SOC}_{\text{St,min}}$ 3. Operate Haber-Bosch synthesis at maximum possible load with maximum grid share
C9	Condition	Is there enough el. energy from RES, H₂ from storage and el. energy from BESS to operate the Haber-Bosch synthesis at minimum load? $\text{C9: } E_{\text{RES},t} + E_{\text{BESS,out},t}^{\text{pot}} + m_{\text{H}_2,\text{St} \rightarrow \text{Syn},t}^{\text{pot}} \geq E_{\text{plant},t}^{\text{min}}$
C9_T	Action	Operate Haber-Bosch synthesis at minimum load through required H ₂ storage and BESS discharge.
C9_F	Action	Initialize Haber-Bosch restart delay timer, thereby blocking the Haber-Bosch synthesis unit until the timer has run out
C10	Condition	Is there enough el. energy from RES to supply the Haber-Bosch synthesis standby demand $E_{\text{Syn,standby}}$? $\text{C10: } E_{\text{RES},t} \geq E_{\text{Syn,standby}}$
C10_T	Action	Supply Haber-Bosch standby demand $E_{\text{Syn,standby}}$ from RES and determine remaining el. energy $E_{\text{RES,remain},t} = E_{\text{RES},t} - E_{\text{Syn,standby}}$
C11	Condition	Is BESS below the minimum required storage capacity? $\text{C11: } \text{SOC}_{\text{BESS},t} \geq \text{SOC}_{\text{BESS,min}}$
C11_T	Action	Charge BESS to minimum required storage and redetermine the remaining available el. energy $E_{\text{RES,remain},t} = E_{\text{Syn,standby}} - E_{\text{BESS,in},t}$
C12	Condition	Is there enough el. energy remaining and enough empty H₂ storage capacity to operate the AEL above minimum load and charge H₂ storage? $\text{C12: } E_{\text{RES,remain},t} \geq P_{\text{El,nom}} \cdot \lambda_{\text{El,min}} \cdot \Delta t \wedge$ $m_{\text{H}_2,\text{St,cap}} - m_{\text{H}_2,\text{St},t-1} \geq m_{\text{H}_2,\text{Co} \rightarrow \text{St},t}$
C12_T	Action	Produce maximum possible amount H ₂ to be stored in H ₂ storage using remaining el. energy to supply AEL and the storage compressor.

Step	Type	Description
		Any leftover el. energy should be used to max charge BESS. Remaining el. energy is allocated to surplus.
C12_F	Action	Use remaining el. energy from RES to max charge BESS. Any remaining el. energy is allocated to surplus.
C13	Condition	Is there enough el. energy from RES and BESS combined to supply standby demand required from Haber-Bosch synthesis? C13: $E_{\text{RES},t} + E_{\text{BESS,out},t}^{\text{pot}} \geq E_{\text{Syn,standby}}$
C13_T	Action	Supply Haber-Bosch synthesis standby demand from RES and BESS combined.
C13_F	Action	Supply Haber-Bosch synthesis standby demand from RES and BESS combined. Any missing el. energy shall be supplied from grid electricity imports from the spot market.

D. Sensitivity Analysis Results – RES Capacity

D.1 Simulation Results – High Wind, High PV

High Wind – RES Capacity	High PV – RES Capacity	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MW	MW	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
200	100	2,099	468	64	3.41	3,179	2,951	831	783	48	2.3	5.7	18	61.9	65.6	67.6	118.0	6.7	796	63.9	49.0	3,131
	200	1,908	468	73	4.00	3,663	3,399	960	894	66	2.3	6.9	21	59.6	64.0	66.0	108.4	7.6	821	52.8	49.0	2,587
	300	1,798	468	81	3.98	4,053	3,761	1,090	987	103	2.1	9.4	22	57.9	63.9	65.7	99.3	8.7	862	44.8	49.1	2,198
	400	1,747	468	87	3.65	4,327	4,014	1,220	1,054	166	1.8	13.6	20	56.5	65.4	66.9	93.5	9.3	868	39.7	49.0	1,945
	500	1,739	468	90	3.42	4,504	4,179	1,349	1,098	252	1.7	18.6	18	55.4	68.1	69.4	88.5	9.9	878	36.7	49.0	1,798
	600	1,748	468	93	3.25	4,639	4,303	1,479	1,131	348	1.5	23.6	17	54.5	71.3	72.5	85.3	10.1	862	34.3	49.0	1,678
300	100	1,746	468	90	5.11	4,519	4,193	1,181	1,092	89	2.6	7.6	29	62.8	67.9	70.1	82.2	8.2	676	40.5	49.1	1,989
	200	1,658	468	99	5.51	4,935	4,579	1,311	1,189	122	2.6	9.3	31	61.0	67.3	69.4	71.2	9.1	649	32.5	49.0	1,590
	300	1,608	468	105	5.42	5,271	4,891	1,440	1,269	171	2.4	11.9	31	59.6	67.6	69.6	63.9	9.8	628	27.0	49.0	1,323
	400	1,593	468	110	5.08	5,492	5,096	1,570	1,324	246	2.1	15.7	29	58.4	69.2	71.0	59.1	10.2	604	23.6	49.0	1,154
	500	1,596	468	113	4.87	5,656	5,248	1,700	1,365	335	2.0	19.7	28	57.4	71.5	73.0	54.7	10.4	569	21.1	49.0	1,031
	600	1,613	468	115	4.72	5,769	5,353	1,830	1,393	437	1.9	23.9	27	56.5	74.2	75.7	51.6	10.6	545	19.2	49.0	938
400	100	1,628	468	111	5.13	5,552	5,152	1,531	1,339	193	2.2	12.6	30	63.3	72.4	74.1	57.9	8.8	511	26.7	49.0	1,308
	200	1,577	468	118	5.42	5,912	5,487	1,661	1,423	238	2.2	14.3	32	61.9	72.2	74.0	47.7	9.7	465	20.3	49.0	995
	300	1,556	468	124	5.26	6,186	5,741	1,791	1,490	301	2.1	16.8	32	60.7	72.9	74.5	42.0	10.3	434	16.9	49.0	828
	400	1,543	468	128	5.03	6,421	5,959	1,921	1,547	374	1.9	19.4	30	59.6	74.0	75.4	35.8	10.0	357	12.8	49.0	627
	500	1,555	468	131	4.84	6,558	6,087	2,050	1,581	469	1.8	22.9	29	58.7	76.1	77.4	32.7	10.0	326	11.1	49.2	544

MW	High Wind – RES Capacity	MW	High PV – RES Capacity	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
				EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
500	600	100	100	1,574	468	133	4.70	6,662	6,183	2,180	1,607	573	1.7	26.3	28	57.9	78.5	79.7	31.2	9.5	295	9.7	49.0	473
		200	200	1,618	468	125	4.43	6,264	5,814	1,882	1,514	368	1.7	19.5	27	63.6	79.1	80.3	40.5	9.8	395	18.4	49.0	902
		300	300	1,581	468	132	4.68	6,606	6,132	2,012	1,594	417	1.7	20.7	28	62.4	78.8	80.0	32.0	9.7	312	12.8	49.0	625
		400	400	1,563	468	137	4.54	6,871	6,378	2,141	1,659	483	1.6	22.5	28	61.4	79.2	80.4	26.5	9.4	249	9.2	49.0	451
		500	500	1,564	468	141	4.28	7,050	6,544	2,271	1,703	568	1.5	25.0	26	60.4	80.6	81.6	22.9	8.8	201	6.9	49.0	338
		600	600	1,580	468	143	4.09	7,157	6,643	2,401	1,730	670	1.4	27.9	25	59.6	82.7	83.7	21.5	8.3	178	5.9	49.0	289
		700	700	1,602	468	145	3.96	7,243	6,724	2,530	1,752	779	1.4	30.8	24	58.8	85.0	85.9	20.7	7.4	153	4.9	49.0	240
600	700	100	100	1,664	468	135	3.74	6,759	6,275	2,232	1,638	594	1.4	26.6	23	63.8	87.0	87.9	29.4	10.2	301	12.8	49.0	627
		200	200	1,629	468	142	3.98	7,099	6,591	2,362	1,718	644	1.4	27.3	24	62.8	86.4	87.2	20.6	9.4	193	7.5	49.0	368
		300	300	1,623	468	146	3.78	7,305	6,783	2,492	1,769	723	1.3	29.0	23	61.9	87.2	88.0	17.7	9.0	158	5.5	49.0	270
		400	400	1,631	468	149	3.53	7,445	6,913	2,621	1,804	817	1.2	31.2	22	61.0	88.7	89.4	15.6	7.9	123	4.1	49.0	198
		500	500	1,650	468	151	3.34	7,530	6,992	2,751	1,826	925	1.1	33.6	21	60.3	90.8	91.5	14.7	7.3	108	3.4	49.0	167
		600	600	1,674	468	152	3.22	7,598	7,056	2,881	1,843	1,038	1.1	36.0	20	59.6	93.2	93.8	13.8	6.6	90	2.8	49.0	135
700	800	100	100	1,742	468	142	3.23	7,102	6,593	2,583	1,724	859	1.1	33.3	19	64.0	95.9	96.5	21.9	12.1	264	9.6	49.3	473
		200	200	1,722	468	147	3.35	7,362	6,836	2,712	1,786	927	1.1	34.2	20	63.1	95.8	96.4	17.3	11.8	203	6.5	49.0	319
		300	300	1,721	468	151	3.18	7,533	6,996	2,842	1,828	1,014	1.1	35.7	20	62.3	96.8	97.4	14.8	11.5	170	5.1	49.0	247
		400	400	1,737	468	153	2.91	7,629	7,085	2,972	1,853	1,119	1.0	37.7	18	61.5	98.6	99.1	14.1	11.9	168	4.7	49.0	228
		500	500	1,759	468	154	2.76	7,702	7,153	3,101	1,872	1,230	0.9	39.7	17	60.8	100.8	101.2	13.3	11.3	151	4.1	49.0	198
		600	600	1,785	468	155	2.64	7,750	7,198	3,231	1,884	1,347	0.9	41.7	16	60.2	103.2	103.6	13.0	11.2	145	3.8	49.0	186

D.2 Simulation Results – High Wind, Low PV

High Wind – RES Capacity		Low PV – RES Capacity																				
MW	MW	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
		EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
200	200	1,992	468	70	3.85	3,492	3,240	919	854	65	2.3	7.0	20	61.4	66.1	68.0	110.4	7.8	861	56.2	49.0	2,754
	300	1,882	468	77	3.94	3,833	3,555	1,028	935	93	2.2	9.1	21	60.2	66.2	68.1	101.9	8.9	906	49.3	49.0	2,413
	400	1,816	468	82	3.75	4,118	3,820	1,137	1,004	133	2.0	11.7	20	59.2	67.1	68.7	96.4	9.0	870	43.2	49.1	2,117
	500	1,798	468	86	3.58	4,307	3,995	1,246	1,050	196	1.8	15.7	19	58.4	69.4	70.8	90.9	9.3	848	39.4	49.1	1,931
	600	1,801	468	89	3.45	4,448	4,126	1,355	1,084	271	1.7	20.0	18	57.8	72.2	73.5	85.5	9.7	832	37.0	49.0	1,811
	700	1,810	468	91	3.35	4,571	4,239	1,464	1,114	350	1.6	23.9	18	57.2	75.2	76.3	81.6	9.8	803	34.5	49.0	1,691
300	200	1,688	468	96	5.51	4,821	4,473	1,269	1,161	108	2.6	8.5	31	62.4	68.2	70.4	71.8	9.2	664	34.0	49.1	1,668
	300	1,636	468	103	5.52	5,143	4,771	1,378	1,238	140	2.5	10.2	31	61.4	68.4	70.4	64.5	9.8	629	28.7	49.0	1,406
	400	1,617	468	107	5.27	5,367	4,980	1,487	1,293	194	2.3	13.1	30	60.6	69.7	71.5	59.1	10.1	596	25.0	49.1	1,225
	500	1,614	468	111	5.11	5,543	5,143	1,596	1,336	260	2.1	16.3	29	59.9	71.5	73.2	55.4	9.8	545	22.0	49.0	1,078
	600	1,631	468	113	4.95	5,649	5,241	1,705	1,362	343	2.0	20.1	28	59.2	74.2	75.7	54.1	9.9	536	20.7	49.0	1,014
	700	1,644	468	115	4.87	5,762	5,345	1,814	1,390	425	2.0	23.4	28	58.7	76.6	78.1	50.6	9.6	486	18.5	49.3	909
400	200	1,592	468	117	5.48	5,843	5,421	1,620	1,406	214	2.2	13.2	32	63.0	72.6	74.3	48.3	9.4	453	21.0	49.0	1,029
	300	1,564	468	122	5.43	6,123	5,682	1,729	1,473	256	2.2	14.8	32	62.2	72.9	74.6	42.7	9.5	405	17.0	49.0	831
	400	1,556	468	126	5.18	6,324	5,869	1,838	1,523	315	2.0	17.1	31	61.4	74.1	75.7	37.6	9.7	364	14.2	49.2	696
	500	1,563	468	129	5.02	6,464	5,999	1,947	1,557	389	1.9	20.0	30	60.8	76.0	77.4	34.8	9.4	326	12.4	49.0	605
	600	1,580	468	131	4.88	6,565	6,092	2,056	1,582	473	1.8	23.0	29	60.2	78.2	79.5	32.1	9.2	295	11.0	49.0	537
	700	1,604	468	133	4.76	6,631	6,154	2,165	1,599	566	1.8	26.1	29	59.7	80.8	82.1	31.9	9.1	290	10.5	49.0	512
500	200	1,590	468	131	4.72	6,546	6,076	1,970	1,580	390	1.8	19.8	28	63.3	79.0	80.2	33.1	9.5	313	13.6	49.0	664
	300	1,574	468	136	4.65	6,793	6,306	2,079	1,639	440	1.7	21.1	28	62.6	79.4	80.6	27.4	9.4	257	10.2	49.0	500

High Wind – RES Capacity																						
Low PV – RES Capacity																						
MW	MW	LCOA EUR/t _{NH3}	Total CapEx MEUR	Average annual NH3 production kt _{NH3} /pa	Average annual NH3 CI gCO ₂ -eq/MJ	Average annual Haber-Bosch FLH FLH	Average annual Electrolysis FLH FLH	Average annual RES production GWh	Average annual RES consumed GWh	Average annual RES surplus GWh	Grid share total consumption %	Curtailment %	Average annual Grid consumption GWh	Specific cost of produced RES EUR/MWh	Specific cost of consumed RES EUR/MWh	Specific cost of consumed RES + Grid EUR/MWh	Average annual Nr of Electrolysis Shutdowns 1	Average Electrolysis Shutdown Duration hours	Average annual Electrolysis downtime hours	Average annual Nr of Haber-Bosch Shutdowns 1	Average Haber-Bosch Shutdown Duration hours	Average annual Haber-Bosch downtime hours
	400	1,577	468	139	4.38	6,946	6,448	2,188	1,678	510	1.6	23.3	27	62.0	80.9	82.0	25.2	9.2	231	8.6	49.0	419
	500	1,588	468	141	4.21	7,067	6,561	2,297	1,708	589	1.5	25.6	26	61.4	82.6	83.6	23.3	8.4	194	7.1	49.0	348
	600	1,609	468	143	4.08	7,140	6,628	2,406	1,726	680	1.4	28.2	25	60.9	84.9	85.8	22.1	8.3	182	6.5	49.0	319
	700	1,633	468	144	3.98	7,198	6,682	2,515	1,741	774	1.4	30.8	24	60.4	87.3	88.2	21.8	8.1	177	6.1	49.0	296
600	200	1,640	468	141	4.00	7,032	6,529	2,320	1,702	619	1.4	26.7	24	63.6	86.7	87.6	22.5	9.4	211	8.4	49.0	412
	300	1,632	468	145	3.88	7,238	6,720	2,429	1,752	678	1.3	27.9	24	63.0	87.3	88.2	18.8	8.9	167	6.2	49.0	304
	400	1,639	468	147	3.63	7,367	6,840	2,538	1,785	754	1.2	29.7	22	62.4	88.8	89.6	17.7	8.0	142	5.2	49.0	252
	500	1,655	468	149	3.45	7,455	6,922	2,647	1,807	841	1.2	31.7	21	61.9	90.7	91.4	16.1	8.0	129	4.5	49.0	221
	600	1,676	468	150	3.33	7,525	6,987	2,756	1,824	932	1.1	33.8	21	61.4	92.8	93.5	15.3	7.2	110	3.8	49.0	186
	700	1,702	468	151	3.23	7,567	7,026	2,865	1,835	1,030	1.1	36.0	20	61.0	95.2	95.8	14.9	7.3	108	3.6	49.0	176
700	200	1,730	468	146	3.40	7,311	6,788	2,671	1,773	898	1.2	33.6	21	63.8	96.1	96.7	18.1	11.4	207	7.0	49.0	341
	300	1,730	468	149	3.24	7,469	6,936	2,780	1,812	968	1.1	34.8	20	63.2	97.0	97.6	16.4	11.4	188	5.9	49.0	289
	400	1,742	468	151	3.00	7,571	7,031	2,889	1,838	1,050	1.0	36.4	19	62.7	98.6	99.1	15.0	11.9	178	5.3	49.0	257
	500	1,762	468	153	2.84	7,637	7,092	2,998	1,855	1,142	0.9	38.1	18	62.3	100.6	101.1	14.6	11.8	172	4.9	49.5	240
	600	1,784	468	154	2.74	7,691	7,143	3,107	1,869	1,238	0.9	39.8	17	61.8	102.8	103.2	13.6	11.7	159	4.4	49.6	216
	700	1,812	468	155	2.66	7,729	7,179	3,216	1,879	1,337	0.9	41.6	17	61.4	105.1	105.5	13.1	11.6	152	4.1	49.0	201

D.3 Simulation Results – Low Wind, High PV

Low Wind – RES Capacity		High PV – RES Capacity																				
MW	MW	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
		EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
200	300	2,352	468	56	2.21	2,806	2,604	764	703	62	1.7	8.0	12	67.1	73.0	74.3	224.5	6.7	1,512	78.4	49.0	3,845
	400	2,217	468	62	1.94	3,110	2,886	894	777	117	1.3	13.1	11	63.9	73.5	74.5	210.9	7.7	1,634	72.2	49.1	3,543
	500	2,161	468	66	1.79	3,322	3,083	1,024	828	195	1.2	19.1	10	61.5	76.0	76.8	206.7	8.1	1,669	67.9	49.1	3,330
	600	2,157	468	69	1.67	3,459	3,209	1,153	861	292	1.0	25.3	9	59.6	79.8	80.6	198.5	8.5	1,691	65.1	49.1	3,197
	700	2,162	468	72	1.58	3,578	3,320	1,283	890	393	0.9	30.6	9	58.2	83.8	84.4	194.8	8.7	1,700	62.4	49.2	3,070
	800	2,184	468	74	1.51	3,676	3,410	1,413	914	499	0.9	35.3	8	56.9	88.0	88.6	192.9	8.8	1,703	60.6	49.1	2,972
300	300	2,183	468	69	2.99	3,425	3,178	952	845	107	1.9	11.2	17	71.6	80.7	82.0	172.0	7.7	1,316	64.2	49.1	3,148
	400	2,069	468	75	2.74	3,745	3,474	1,081	922	159	1.6	14.7	15	68.4	80.2	81.3	160.0	8.4	1,340	57.6	49.1	2,825
	500	2,031	468	79	2.60	3,955	3,669	1,211	973	238	1.4	19.6	14	65.9	82.0	83.0	154.2	8.7	1,335	53.1	49.0	2,602
	600	2,035	468	82	2.45	4,090	3,794	1,341	1,006	335	1.3	24.9	13	63.9	85.1	86.0	148.0	9.2	1,357	50.7	49.1	2,489
	700	2,047	468	84	2.36	4,210	3,905	1,471	1,035	435	1.2	29.6	13	62.2	88.4	89.1	144.9	9.3	1,340	48.6	49.0	2,379
	800	2,070	468	86	2.29	4,301	3,990	1,600	1,058	543	1.2	33.9	13	60.8	92.0	92.7	142.4	9.4	1,340	46.8	49.0	2,293
400	300	2,058	468	81	3.62	4,049	3,757	1,139	989	150	2.0	13.1	20	74.6	85.9	87.2	133.1	8.2	1,089	51.1	49.1	2,509
	400	1,984	468	87	3.34	4,346	4,031	1,269	1,062	207	1.7	16.3	19	71.6	85.6	86.7	122.3	9.0	1,100	45.2	49.2	2,225
	500	1,957	468	91	3.16	4,550	4,220	1,399	1,111	287	1.6	20.6	18	69.1	87.0	88.0	114.8	9.4	1,079	41.4	49.1	2,034
	600	1,956	468	94	3.03	4,703	4,363	1,528	1,149	380	1.5	24.8	17	67.1	89.3	90.1	110.9	9.5	1,051	38.8	49.0	1,899
	700	1,965	468	96	2.94	4,824	4,474	1,658	1,178	480	1.4	29.0	16	65.4	92.0	92.8	107.8	9.6	1,032	36.7	49.0	1,798
	800	1,985	468	98	2.86	4,915	4,559	1,788	1,200	588	1.3	32.9	16	63.9	95.2	95.9	104.6	9.8	1,023	35.2	49.1	1,727
500	300	1,997	468	92	4.03	4,607	4,274	1,327	1,120	207	2.0	15.6	23	76.8	91.0	92.2	106.5	8.1	862	40.3	49.0	1,972
	400	1,936	468	98	3.70	4,892	4,539	1,456	1,190	267	1.7	18.3	21	74.0	90.5	91.6	97.8	8.7	854	35.4	49.0	1,732

Low Wind – RES Capacity																						
High PV – RES Capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MW	MW	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
	500	1,906	468	102	3.54	5,117	4,747	1,586	1,245	342	1.6	21.5	20	71.6	91.3	92.2	90.0	8.9	798	31.2	49.0	1,529
	600	1,909	468	105	3.39	5,261	4,880	1,716	1,280	436	1.5	25.4	19	69.6	93.3	94.2	87.6	8.9	779	28.9	49.0	1,416
	700	1,927	468	107	3.29	5,365	4,977	1,846	1,305	541	1.4	29.3	19	67.9	96.0	96.7	83.8	9.1	760	27.2	49.0	1,333
	800	1,939	468	109	3.22	5,471	5,075	1,975	1,331	645	1.4	32.6	18	66.4	98.5	99.2	80.4	9.0	720	25.3	49.0	1,240
600	300	1,984	468	101	4.20	5,063	4,698	1,514	1,228	286	1.9	18.9	24	78.4	96.7	97.7	85.7	8.6	740	33.0	49.0	1,617
	400	1,928	468	107	3.90	5,350	4,964	1,644	1,298	346	1.7	21.0	22	75.8	96.0	96.9	77.1	9.1	699	28.1	49.0	1,374
	500	1,913	468	111	3.71	5,550	5,148	1,774	1,347	427	1.5	24.1	21	73.5	96.8	97.7	71.2	9.3	661	25.0	49.0	1,225
	600	1,915	468	114	3.56	5,691	5,280	1,903	1,382	522	1.5	27.4	20	71.6	98.6	99.4	66.9	9.4	626	22.6	49.0	1,107
	700	1,921	468	116	3.47	5,819	5,398	2,033	1,413	620	1.4	30.5	20	69.9	100.6	101.3	63.6	9.1	578	20.4	49.0	997
	800	1,945	468	118	3.38	5,901	5,475	2,163	1,433	730	1.3	33.8	19	68.4	103.3	103.9	62.2	8.9	554	19.2	49.0	938
700	300	2,041	468	107	4.15	5,330	4,945	1,702	1,292	409	1.8	24.1	24	79.7	105.0	105.8	77.6	10.8	834	31.4	49.0	1,536
	400	1,989	468	112	3.85	5,610	5,205	1,831	1,361	471	1.6	25.7	22	77.3	104.0	104.7	68.9	11.4	787	27.3	49.0	1,335
	500	1,984	468	115	3.64	5,771	5,355	1,961	1,401	560	1.5	28.6	21	75.1	105.2	105.8	64.9	11.8	766	25.1	49.1	1,230
	600	1,989	468	118	3.51	5,905	5,479	2,091	1,434	657	1.4	31.4	20	73.2	106.8	107.4	61.5	11.9	733	23.1	49.1	1,134
	700	2,018	468	119	3.38	5,963	5,533	2,221	1,449	772	1.3	34.8	20	71.6	109.8	110.3	61.2	12.4	760	23.1	49.1	1,132
	800	2,039	468	121	3.28	6,046	5,610	2,350	1,469	881	1.3	37.5	19	70.1	112.2	112.7	58.6	12.5	732	22.0	49.1	1,078

D.4 Simulation Results – Low Wind, Low PV

Low Wind – RES Capacity		Low PV – RES Capacity																				
MW	MW	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
		EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
300	300	2,315	468	64	2.75	3,206	2,974	890	794	95	1.9	10.7	15	75.3	84.3	85.6	182.0	7.3	1,320	69.6	49.1	3,417
	400	2,207	468	70	2.60	3,481	3,230	999	861	138	1.6	13.8	14	72.5	84.2	85.2	171.6	7.9	1,362	64.1	49.0	3,138
	500	2,158	468	74	2.48	3,683	3,417	1,108	909	198	1.5	17.9	14	70.3	85.6	86.6	161.8	8.3	1,339	59.7	49.0	2,925
	600	2,139	468	77	2.37	3,837	3,559	1,217	946	270	1.4	22.2	13	68.5	88.0	88.9	155.4	8.6	1,332	56.4	49.1	2,765
	700	2,143	468	79	2.29	3,958	3,671	1,325	976	350	1.3	26.4	13	67.0	91.0	91.7	153.5	8.6	1,326	53.9	49.1	2,643
	800	2,152	468	81	2.25	4,062	3,767	1,434	1,001	434	1.2	30.2	12	65.7	94.2	94.9	147.6	8.8	1,303	51.6	49.0	2,530
400	300	2,175	468	76	3.31	3,799	3,524	1,077	932	145	1.9	13.5	18	77.9	90.0	91.1	142.1	8.1	1,148	57.0	49.2	2,802
	400	2,085	468	82	3.18	4,091	3,795	1,186	1,002	184	1.7	15.5	18	75.3	89.1	90.2	130.7	8.5	1,114	51.1	49.0	2,503
	500	2,056	468	86	3.04	4,279	3,969	1,295	1,048	247	1.6	19.1	17	73.2	90.5	91.4	125.4	8.8	1,098	47.6	49.1	2,334
	600	2,040	468	89	2.96	4,449	4,127	1,404	1,089	315	1.5	22.5	17	71.4	92.0	92.9	119.1	8.8	1,049	44.0	49.1	2,160
	700	2,039	468	92	2.92	4,579	4,247	1,513	1,120	393	1.4	26.0	16	69.8	94.4	95.2	113.2	9.0	1,016	41.0	49.1	2,013
	800	2,056	468	93	2.86	4,670	4,331	1,622	1,142	480	1.4	29.6	16	68.5	97.3	98.0	110.8	9.1	1,007	39.3	49.2	1,932
500	300	2,090	468	87	3.73	4,365	4,050	1,265	1,064	200	1.9	15.8	21	79.7	94.6	95.7	113.7	8.1	926	45.6	49.0	2,236
	400	2,020	468	93	3.58	4,647	4,311	1,374	1,132	241	1.7	17.6	20	77.3	93.8	94.8	103.8	8.5	885	40.4	49.0	1,976
	500	1,980	468	97	3.48	4,872	4,519	1,483	1,186	296	1.6	20.0	19	75.3	94.1	95.0	94.6	8.5	805	35.6	49.0	1,743
	600	1,975	468	100	3.37	5,024	4,661	1,592	1,223	368	1.5	23.1	19	73.6	95.7	96.5	90.9	8.5	772	33.0	49.0	1,613
	700	1,984	468	103	3.31	5,139	4,767	1,701	1,251	450	1.5	26.4	19	72.1	97.9	98.7	88.8	8.4	748	31.2	48.9	1,527
	800	2,001	468	105	3.26	5,232	4,853	1,810	1,274	536	1.4	29.6	18	70.7	100.5	101.2	86.8	8.4	726	29.6	48.9	1,449
600	300	2,061	468	97	4.00	4,848	4,499	1,452	1,178	274	1.9	18.9	23	81.0	99.8	100.8	90.0	8.7	784	37.3	49.0	1,826
	400	2,000	468	102	3.82	5,123	4,753	1,561	1,244	317	1.7	20.3	22	78.8	98.9	99.8	82.0	8.7	717	32.3	48.9	1,581

Low Wind – RES Capacity																						
Low PV – RES Capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MW	MW	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
	500	1,978	468	106	3.68	5,316	4,932	1,670	1,291	379	1.6	22.7	21	76.9	99.5	100.3	77.1	8.7	667	28.9	48.9	1,414
	600	1,979	468	109	3.56	5,452	5,059	1,779	1,325	454	1.5	25.5	20	75.3	101.1	101.9	73.1	8.8	643	26.9	48.9	1,314
	700	1,988	468	111	3.48	5,565	5,163	1,888	1,352	536	1.4	28.4	20	73.8	103.1	103.8	70.0	8.7	611	25.0	48.9	1,221
	800	2,001	468	113	3.45	5,662	5,253	1,997	1,375	622	1.4	31.1	20	72.5	105.3	105.9	68.5	8.5	580	23.3	48.9	1,140
700	300	2,105	468	103	3.96	5,139	4,769	1,640	1,248	392	1.8	23.9	23	82.0	107.8	108.5	80.6	10.5	844	34.7	49.1	1,703
	400	2,056	468	108	3.79	5,396	5,008	1,749	1,311	438	1.6	25.0	22	80.0	106.8	107.5	75.3	10.5	787	30.7	49.1	1,505
	500	2,042	468	111	3.63	5,562	5,161	1,858	1,351	507	1.5	27.3	21	78.3	107.6	108.3	70.6	10.8	762	28.3	49.1	1,390
	600	2,046	468	114	3.52	5,681	5,271	1,967	1,380	586	1.5	29.8	20	76.7	109.3	109.9	67.4	11.0	741	26.7	49.1	1,311
	700	2,071	468	115	3.42	5,747	5,333	2,076	1,397	679	1.4	32.7	20	75.3	111.9	112.4	65.2	11.8	771	26.4	49.1	1,296
	800	2,077	468	117	3.38	5,856	5,434	2,185	1,423	762	1.4	34.9	20	74.0	113.7	114.1	63.1	11.4	717	24.5	49.2	1,203
800	300	2,114	468	111	4.04	5,532	5,134	1,827	1,341	486	1.7	26.6	23	82.8	112.8	113.5	63.0	10.6	669	27.9	49.1	1,370
	400	2,067	468	116	3.83	5,785	5,369	1,936	1,403	533	1.6	27.5	22	81.0	111.7	112.3	56.4	10.8	607	24.0	49.1	1,176
	500	2,057	468	119	3.66	5,944	5,516	2,045	1,442	603	1.5	29.5	21	79.3	112.5	113.0	52.1	11.2	582	22.0	49.1	1,078
	600	2,053	468	122	3.57	6,083	5,645	2,154	1,476	678	1.4	31.5	21	77.9	113.6	114.1	48.2	11.0	532	19.8	49.1	973
	700	2,064	468	124	3.49	6,180	5,736	2,263	1,500	763	1.3	33.7	20	76.5	115.4	115.9	46.9	10.9	510	18.8	49.0	919
	800	2,083	468	125	3.41	6,250	5,800	2,372	1,517	855	1.3	36.0	20	75.3	117.7	118.1	45.2	11.1	503	18.1	49.0	884

E. Sensitivity Analysis Results – Storage Capacity

E.1 Simulation Results – High Wind (400 MW), High PV (400 MW)

BESS capacity																						
H2 Storage capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MWh	t _{H2}	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
0	0	3,136	382	58	2.15	2,899	2,690	1,921	732	1,189	1.8	61.9	14	59.6	156.5	156.3	74.4	75.0	5,579	74.4	75.0	5,579
	20	1,684	400	111	4.24	5,537	5,137	1,921	1,342	578	1.9	30.1	26	59.6	85.3	86.5	76.9	21.1	1,624	39.8	49.4	1,967
	40	1,564	409	120	4.66	6,022	5,589	1,921	1,455	466	1.9	24.2	28	59.6	78.7	80.0	69.4	13.9	966	25.7	49.2	1,264
	60	1,531	418	124	4.84	6,205	5,760	1,921	1,497	423	1.9	22.0	29	59.6	76.4	77.9	64.9	11.2	727	20.0	49.1	980
	80	1,522	428	126	4.91	6,284	5,833	1,921	1,515	405	1.9	21.1	30	59.6	75.5	77.0	63.0	10.0	632	17.5	49.1	858
	100	1,521	437	127	4.95	6,327	5,874	1,921	1,526	395	1.9	20.6	30	59.6	75.0	76.5	61.9	9.4	581	16.5	49.1	809
1,000	0	2,067	655	111	4.22	5,546	5,145	1,921	1,350	571	1.9	29.7	26	59.6	84.8	86.0	40.4	49.0	1,977	40.4	49.0	1,977
	20	1,836	673	127	4.97	6,333	5,877	1,921	1,529	392	1.9	20.4	30	59.6	74.9	76.3	40.2	15.6	627	15.5	49.0	757
	40	1,794	682	131	5.19	6,532	6,063	1,921	1,573	347	1.9	18.1	31	59.6	72.7	74.2	30.2	9.3	281	8.3	49.0	407
	60	1,789	691	132	5.28	6,593	6,120	1,921	1,587	334	1.9	17.4	31	59.6	72.1	73.6	26.4	6.6	173	5.7	49.0	277
	80	1,787	701	133	5.33	6,630	6,154	1,921	1,595	326	1.9	17.0	31	59.6	71.8	73.3	23.5	5.3	126	4.4	49.0	213
	100	1,790	710	133	5.36	6,655	6,177	1,921	1,600	320	1.9	16.7	31	59.6	71.5	73.0	21.4	4.5	96	3.3	49.0	162
2,000	0	2,196	928	125	4.81	6,268	5,817	1,921	1,520	401	1.9	20.9	29	59.6	75.3	76.7	19.4	49.0	948	19.4	49.0	948
	20	2,126	946	131	5.22	6,568	6,097	1,921	1,584	337	1.9	17.5	31	59.6	72.3	73.7	24.4	13.2	322	7.7	49.0	377
	40	2,123	955	132	5.29	6,611	6,137	1,921	1,592	329	1.9	17.1	31	59.6	71.9	73.4	23.0	8.0	184	5.1	49.0	250
	60	2,121	964	133	5.36	6,648	6,171	1,921	1,599	321	1.9	16.7	31	59.6	71.6	73.1	21.2	5.8	122	3.3	49.7	164
	80	2,127	974	133	5.38	6,656	6,178	1,921	1,601	319	1.9	16.6	31	59.6	71.5	73.0	20.6	4.9	101	2.9	49.0	142

BESS capacity																							
H2 Storage capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime	
MWh	t _{H2}	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours	
100	100	2,132	983	133	5.39	6,667	6,189	1,921	1,603	317	1.9	16.5	32	59.6	71.4	72.9	19.7	4.2	83	2.5	49.0	123	
	3,000	0	2,456	1,201	131	5.05	6,559	6,090	1,921	1,589	332	1.9	17.3	31	59.6	72.1	73.5	10.9	49.0	532	10.9	49.0	532
	20	2,445	1,219	133	5.31	6,655	6,179	1,921	1,605	316	1.9	16.5	31	59.6	71.3	72.8	18.3	11.1	203	4.8	49.5	238	
	40	2,452	1,228	133	5.36	6,663	6,186	1,921	1,604	316	1.9	16.5	31	59.6	71.3	72.9	18.7	7.0	131	3.2	49.8	157	
	60	2,459	1,237	133	5.39	6,667	6,189	1,921	1,604	316	1.9	16.5	31	59.6	71.3	72.9	19.4	5.2	100	2.6	49.0	125	
	80	2,468	1,247	133	5.40	6,669	6,190	1,921	1,604	316	1.9	16.5	32	59.6	71.4	72.9	19.3	4.6	88	2.4	49.0	115	
	100	2,476	1,256	133	5.40	6,671	6,192	1,921	1,604	316	1.9	16.5	32	59.6	71.3	72.9	19.2	4.2	80	2.3	49.0	110	
4,000	0	2,757	1,474	134	5.18	6,690	6,211	1,921	1,619	301	1.9	15.7	31	59.6	70.7	72.2	6.8	49.0	333	6.8	49.0	333	
	20	2,773	1,492	134	5.35	6,702	6,223	1,921	1,616	305	1.9	15.9	31	59.6	70.8	72.4	15.2	9.6	146	3.4	49.0	164	
	40	2,790	1,501	134	5.39	6,684	6,206	1,921	1,609	311	1.9	16.2	32	59.6	71.1	72.6	17.2	6.2	107	2.5	49.0	123	
	60	2,802	1,510	133	5.40	6,674	6,196	1,921	1,606	315	1.9	16.4	32	59.6	71.3	72.8	18.6	5.0	93	2.3	49.0	110	
	80	2,812	1,520	133	5.40	6,670	6,192	1,921	1,604	316	1.9	16.5	31	59.6	71.3	72.9	19.1	4.5	86	2.3	49.0	110	
	100	2,820	1,529	133	5.40	6,672	6,193	1,921	1,605	316	1.9	16.4	32	59.6	71.3	72.8	19.2	4.1	79	2.2	49.0	105	
5,000	0	3,067	1,747	135	5.24	6,767	6,284	1,921	1,638	283	1.9	14.7	32	59.6	69.9	71.4	4.6	49.0	223	4.6	49.0	223	
	20	3,107	1,765	135	5.38	6,725	6,245	1,921	1,621	299	1.9	15.6	32	59.6	70.6	72.1	13.8	8.6	118	2.7	49.0	130	
	40	3,131	1,774	134	5.39	6,691	6,212	1,921	1,611	310	1.9	16.1	32	59.6	71.0	72.6	16.7	5.9	99	2.3	49.0	110	
	60	3,146	1,783	134	5.40	6,676	6,198	1,921	1,607	314	1.9	16.3	32	59.6	71.2	72.8	18.6	4.9	91	2.2	49.0	105	
	80	3,155	1,793	133	5.40	6,673	6,195	1,921	1,605	315	1.9	16.4	32	59.6	71.3	72.8	18.9	4.4	83	2.1	49.0	103	
	100	3,163	1,802	134	5.41	6,675	6,197	1,921	1,606	315	1.9	16.4	32	59.6	71.3	72.8	18.8	4.1	76	2.0	49.0	98	

E.2 Simulation Results – High Wind (400 MW), Low PV (400 MW)

BESS capacity																						
H2 Storage capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailement	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MWh	t _{H2}	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
0	0	3,162	382	57	2.20	2,840	2,634	1,838	717	1,121	1.9	61.0	14	61.4	157.5	157.3	74.2	75.9	5,633	74.2	75.9	5,633
	20	1,686	400	110	4.43	5,493	5,096	1,838	1,331	507	2.0	27.6	27	61.4	84.9	86.2	78.2	20.0	1,566	39.8	49.3	1,962
	40	1,569	409	119	4.83	5,952	5,524	1,838	1,437	401	2.0	21.8	29	61.4	78.6	80.0	69.2	13.5	931	26.1	49.1	1,281
	60	1,537	418	123	5.00	6,134	5,694	1,838	1,479	359	2.0	19.5	30	61.4	76.3	77.8	65.0	10.7	692	20.4	49.2	1,005
	80	1,532	428	124	5.07	6,200	5,756	1,838	1,494	343	2.0	18.7	31	61.4	75.6	77.0	63.2	9.7	614	18.0	49.3	887
	100	1,531	437	125	5.11	6,243	5,795	1,838	1,504	333	2.0	18.1	31	61.4	75.1	76.6	61.9	9.1	562	16.8	49.1	826
1,000	0	2,095	655	109	4.35	5,438	5,045	1,838	1,323	514	2.0	28.0	27	61.4	85.3	86.6	41.9	49.0	2,053	41.9	49.0	2,053
	20	1,866	673	124	5.07	6,191	5,744	1,838	1,494	344	2.0	18.7	30	61.4	75.6	77.1	45.8	15.4	703	18.1	49.0	884
	40	1,816	682	128	5.34	6,424	5,963	1,838	1,547	291	2.0	15.8	32	61.4	73.0	74.5	32.6	9.3	303	10.0	49.0	488
	60	1,807	691	130	5.41	6,485	6,020	1,838	1,560	277	2.0	15.1	32	61.4	72.4	73.9	28.1	6.9	193	7.4	49.0	360
	80	1,806	701	131	5.47	6,527	6,059	1,838	1,570	268	2.0	14.6	32	61.4	71.9	73.5	24.9	5.3	133	5.6	49.0	274
	100	1,808	710	131	5.51	6,553	6,082	1,838	1,575	263	2.0	14.3	32	61.4	71.7	73.3	22.7	4.4	100	4.5	49.0	221
2,000	0	2,221	928	123	4.97	6,170	5,726	1,838	1,495	343	2.0	18.6	30	61.4	75.5	77.0	20.7	49.0	1,014	20.7	49.0	1,014
	20	2,158	946	129	5.34	6,444	5,982	1,838	1,554	284	2.0	15.5	32	61.4	72.7	74.2	27.7	13.9	386	9.8	49.3	483
	40	2,145	955	130	5.45	6,511	6,044	1,838	1,567	270	2.0	14.7	32	61.4	72.0	73.6	23.8	8.9	212	6.4	49.0	314
	60	2,147	964	131	5.50	6,536	6,067	1,838	1,572	266	2.0	14.4	32	61.4	71.8	73.4	22.7	6.4	145	5.0	49.0	245
	80	2,149	974	131	5.54	6,556	6,085	1,838	1,576	261	2.0	14.2	32	61.4	71.6	73.2	21.8	5.2	114	4.1	49.0	201
	100	2,153	983	131	5.55	6,569	6,097	1,838	1,579	259	2.0	14.1	32	61.4	71.5	73.1	20.5	4.5	93	3.6	49.0	174
3,000	0	2,499	1,201	129	5.18	6,427	5,966	1,838	1,556	282	2.0	15.3	31	61.4	72.6	74.1	12.9	49.0	630	12.9	49.0	630
	20	2,476	1,219	131	5.46	6,543	6,075	1,838	1,577	261	2.0	14.2	32	61.4	71.6	73.2	20.5	12.2	250	6.4	49.0	311

BESS capacity																						
MWh	t _{H2}	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
		EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
	40	2,484	1,228	131	5.50	6,552	6,083	1,838	1,577	261	2.0	14.2	32	61.4	71.6	73.2	20.3	8.2	165	4.8	49.0	233
	60	2,488	1,237	131	5.55	6,564	6,094	1,838	1,579	259	2.0	14.1	32	61.4	71.5	73.1	20.2	6.1	123	3.8	49.0	186
	80	2,494	1,247	131	5.56	6,571	6,100	1,838	1,580	258	2.0	14.0	32	61.4	71.5	73.0	20.2	5.1	103	3.4	49.0	167
	100	2,501	1,256	132	5.56	6,576	6,104	1,838	1,581	257	2.0	14.0	32	61.4	71.4	73.0	19.8	4.6	90	3.2	49.0	154
4,000	0	2,797	1,474	131	5.31	6,573	6,103	1,838	1,590	247	2.0	13.5	32	61.4	71.0	72.6	8.5	49.0	417	8.5	49.0	417
	20	2,816	1,492	132	5.48	6,577	6,107	1,838	1,585	252	2.0	13.7	32	61.4	71.2	72.8	17.9	11.8	212	5.2	49.0	255
	40	2,824	1,501	132	5.54	6,579	6,108	1,838	1,583	254	2.0	13.8	32	61.4	71.3	72.9	18.6	7.4	138	3.8	49.0	186
	60	2,833	1,510	132	5.56	6,579	6,107	1,838	1,582	255	2.0	13.9	32	61.4	71.4	72.9	19.0	5.8	110	3.3	49.0	159
	80	2,841	1,520	132	5.57	6,578	6,106	1,838	1,582	256	2.0	13.9	32	61.4	71.4	73.0	19.0	5.2	98	3.0	49.0	147
	100	2,847	1,529	132	5.57	6,581	6,109	1,838	1,582	256	2.0	13.9	32	61.4	71.4	72.9	18.9	4.6	86	2.9	49.0	142
5,000	0	3,116	1,747	133	5.37	6,637	6,163	1,838	1,606	232	2.0	12.6	33	61.4	70.3	71.9	6.4	49.0	311	6.4	49.0	311
	20	3,153	1,765	132	5.52	6,608	6,136	1,838	1,593	245	2.0	13.3	32	61.4	70.9	72.5	15.9	10.5	167	4.1	49.0	201
	40	3,166	1,774	132	5.56	6,596	6,123	1,838	1,587	250	2.0	13.6	32	61.4	71.1	72.7	17.3	7.1	123	3.3	49.0	159
	60	3,182	1,783	132	5.56	6,580	6,108	1,838	1,583	255	2.0	13.9	32	61.4	71.3	72.9	18.6	5.9	109	3.1	49.0	152
	80	3,187	1,793	132	5.57	6,583	6,110	1,838	1,583	255	2.0	13.9	32	61.4	71.3	72.9	18.6	5.1	94	2.8	49.0	137
	100	3,195	1,802	132	5.58	6,584	6,112	1,838	1,583	255	2.0	13.9	32	61.4	71.3	72.9	18.7	4.4	83	2.7	49.0	130

E.3 Simulation Results – Low Wind (500 MW), High PV (500 MW)

BESS capacity																						
H2 Storage capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MWh	t _{H2}	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
0	0	7,432	382	23	0.87	1,170	1,084	1,586	328	1,258	1.6	79.3	5	71.6	345.9	342.6	64.8	115.2	7,463	64.8	115.2	7,463
	20	2,399	400	76	2.61	3,816	3,539	1,586	943	643	1.6	40.6	15	71.6	120.5	120.9	143.5	21.1	3,033	73.0	49.9	3,642
	40	2,038	409	91	3.13	4,549	4,220	1,586	1,113	473	1.6	29.9	18	71.6	102.1	102.8	142.4	13.5	1,918	51.2	49.4	2,529
	60	1,933	418	97	3.34	4,832	4,484	1,586	1,178	408	1.6	25.7	19	71.6	96.4	97.2	140.5	10.3	1,441	41.1	49.8	2,048
	80	1,890	428	99	3.45	4,975	4,618	1,586	1,211	375	1.6	23.6	20	71.6	93.8	94.7	137.5	8.8	1,214	36.0	50.0	1,798
	100	1,875	437	101	3.51	5,053	4,690	1,586	1,230	357	1.6	22.5	20	71.6	92.4	93.3	134.6	8.1	1,094	33.7	50.0	1,683
1,000	0	2,924	655	77	2.59	3,837	3,557	1,586	956	630	1.6	39.7	15	71.6	118.8	119.3	74.4	49.0	3,642	74.4	49.0	3,642
	20	2,296	673	100	3.47	4,985	4,622	1,586	1,217	369	1.6	23.2	19	71.6	93.3	94.2	91.2	15.9	1,447	35.4	49.0	1,735
	40	2,161	682	107	3.81	5,342	4,956	1,586	1,298	288	1.6	18.2	21	71.6	87.5	88.5	72.1	8.9	644	20.4	49.0	997
	60	2,125	691	109	4.00	5,474	5,079	1,586	1,327	260	1.6	16.4	21	71.6	85.6	86.6	60.5	5.5	332	13.2	49.0	644
	80	2,120	701	110	4.09	5,521	5,124	1,586	1,337	249	1.6	15.7	22	71.6	85.0	86.0	55.0	3.9	213	10.1	49.0	492
	100	2,126	710	111	4.13	5,535	5,136	1,586	1,339	247	1.6	15.6	22	71.6	84.8	85.8	51.1	3.3	170	8.4	49.0	412
2,000	0	2,740	928	99	3.28	4,946	4,586	1,586	1,218	368	1.5	23.2	19	71.6	93.2	94.1	40.6	49.0	1,989	40.6	49.0	1,989
	20	2,535	946	109	3.84	5,428	5,036	1,586	1,323	263	1.6	16.6	21	71.6	85.9	86.9	59.2	13.7	810	19.7	49.0	965
	40	2,502	955	111	4.03	5,545	5,145	1,586	1,346	240	1.6	15.1	22	71.6	84.4	85.4	51.5	7.3	378	11.4	49.0	556
	60	2,500	964	111	4.13	5,572	5,171	1,586	1,350	236	1.6	14.9	22	71.6	84.1	85.2	47.5	4.7	225	7.8	49.0	382
	80	2,514	974	111	4.16	5,568	5,168	1,586	1,348	238	1.6	15.0	22	71.6	84.3	85.3	46.9	3.8	177	6.7	49.0	328
	100	2,522	983	111	4.21	5,574	5,173	1,586	1,349	238	1.6	15.0	22	71.6	84.2	85.3	43.9	3.2	141	5.3	49.0	259
3,000	0	2,947	1,201	108	3.58	5,385	4,995	1,586	1,323	264	1.5	16.6	21	71.6	85.9	86.9	26.7	49.0	1,306	26.7	49.0	1,306
	20	2,864	1,219	112	4.00	5,618	5,213	1,586	1,368	218	1.6	13.8	22	71.6	83.0	84.1	43.8	11.8	516	12.6	49.0	617

BESS capacity																						
MWh	t _{H2}	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
		EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
	40	2,861	1,228	113	4.14	5,651	5,245	1,586	1,371	215	1.6	13.6	22	71.6	82.8	83.9	40.4	6.0	241	6.9	49.0	338
	60	2,889	1,237	112	4.20	5,617	5,214	1,586	1,361	226	1.6	14.2	22	71.6	83.5	84.5	41.2	4.2	172	5.2	49.0	255
	80	2,906	1,246	112	4.24	5,603	5,200	1,586	1,356	230	1.6	14.5	22	71.6	83.7	84.8	40.1	3.5	140	4.1	48.7	200
	100	2,924	1,256	112	4.27	5,589	5,187	1,586	1,352	234	1.6	14.8	22	71.6	84.0	85.1	40.7	3.3	134	3.6	48.6	175
4,000	0	3,235	1,474	113	3.76	5,627	5,221	1,586	1,380	206	1.5	13.0	22	71.6	82.3	83.3	18.9	49.0	924	18.9	49.0	924
	20	3,212	1,492	115	4.09	5,727	5,314	1,586	1,394	192	1.6	12.1	22	71.6	81.5	82.5	35.4	10.0	354	8.7	49.0	426
	40	3,244	1,501	114	4.18	5,692	5,283	1,586	1,381	205	1.6	12.9	22	71.6	82.2	83.3	35.5	5.4	191	5.0	49.0	245
	60	3,281	1,510	113	4.25	5,645	5,239	1,586	1,367	219	1.6	13.8	22	71.6	83.1	84.1	36.8	3.9	142	3.6	48.6	175
	80	3,306	1,519	112	4.27	5,619	5,214	1,586	1,360	226	1.6	14.3	22	71.6	83.5	84.6	38.2	3.4	130	3.2	49.0	154
	100	3,325	1,529	112	4.29	5,606	5,203	1,586	1,356	230	1.6	14.5	22	71.6	83.8	84.8	38.6	3.1	120	2.6	49.0	127
5,000	0	3,557	1,747	115	3.86	5,767	5,352	1,586	1,413	173	1.5	10.9	22	71.6	80.4	81.4	13.7	49.0	671	13.7	49.0	671
	20	3,574	1,765	116	4.14	5,789	5,374	1,586	1,409	177	1.6	11.2	22	71.6	80.6	81.7	31.3	8.4	262	6.4	49.0	311
	40	3,629	1,774	114	4.22	5,719	5,309	1,586	1,387	199	1.6	12.5	22	71.6	81.9	82.9	33.1	4.6	152	3.8	48.6	182
	60	3,678	1,783	113	4.25	5,658	5,252	1,586	1,370	216	1.6	13.6	22	71.6	82.9	83.9	35.8	3.7	133	3.0	49.0	145
	80	3,705	1,792	113	4.28	5,632	5,227	1,586	1,363	223	1.6	14.1	22	71.6	83.3	84.4	37.4	3.2	119	2.5	49.0	123
	100	3,728	1,802	112	4.29	5,613	5,209	1,586	1,358	228	1.6	14.4	22	71.6	83.6	84.7	38.3	2.9	113	2.2	49.0	108

E.4 Simulation Results – Low Wind (500 MW), Low PV (600 MW)

BESS capacity																						
H2 Storage capacity		LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailement	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
MWh	t _{H2}	EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
0	0	7,525	382	23	0.86	1,163	1,078	1,592	327	1,265	1.6	79.5	5	73.6	358.3	354.9	62.7	119.2	7,471	62.7	119.2	7,471
	20	2,475	400	75	2.51	3,760	3,487	1,592	930	662	1.6	41.6	15	73.6	125.9	126.3	150.8	19.6	2,956	74.1	50.0	3,701
	40	2,119	409	89	2.95	4,449	4,127	1,592	1,090	502	1.6	31.5	17	73.6	107.4	108.1	145.8	13.0	1,890	52.5	50.1	2,633
	60	1,991	418	95	3.19	4,771	4,427	1,592	1,164	427	1.6	26.8	18	73.6	100.6	101.3	141.4	9.6	1,352	41.9	49.7	2,083
	80	1,952	428	98	3.30	4,905	4,553	1,592	1,196	396	1.6	24.9	19	73.6	97.9	98.7	138.7	8.3	1,146	37.4	49.7	1,855
	100	1,935	437	100	3.36	4,981	4,624	1,592	1,213	378	1.6	23.8	19	73.6	96.5	97.3	136.0	7.6	1,034	34.6	50.1	1,732
1,000	0	3,011	655	76	2.47	3,783	3,508	1,592	944	647	1.5	40.7	14	73.6	124.0	124.4	75.4	49.0	3,692	75.4	49.0	3,692
	20	2,369	673	98	3.32	4,920	4,562	1,592	1,203	388	1.5	24.4	18	73.6	97.3	98.1	94.8	14.8	1,404	36.8	49.0	1,799
	40	2,247	682	105	3.61	5,227	4,850	1,592	1,272	320	1.5	20.1	20	73.6	92.0	92.9	77.3	8.5	660	23.4	48.9	1,142
	60	2,218	691	107	3.75	5,329	4,945	1,592	1,294	298	1.5	18.7	20	73.6	90.5	91.4	67.5	6.0	403	17.5	49.0	855
	80	2,211	701	107	3.81	5,374	4,986	1,592	1,303	288	1.5	18.1	20	73.6	89.8	90.8	61.3	4.7	289	14.9	49.2	730
	100	2,214	710	108	3.87	5,391	5,003	1,592	1,307	285	1.5	17.9	20	73.6	89.6	90.5	57.0	4.4	248	13.3	48.9	649
2,000	0	2,795	928	99	3.19	4,935	4,577	1,592	1,217	375	1.5	23.5	18	73.6	96.2	97.0	40.2	49.0	1,969	40.2	49.0	1,969
	20	2,619	946	107	3.65	5,336	4,951	1,592	1,302	289	1.5	18.2	20	73.6	89.9	90.8	63.2	13.3	838	22.0	48.9	1,076
	40	2,599	955	108	3.80	5,408	5,019	1,592	1,315	277	1.5	17.4	20	73.6	89.0	90.0	57.7	8.2	474	15.7	49.0	767
	60	2,607	964	108	3.86	5,412	5,022	1,592	1,313	278	1.5	17.5	20	73.6	89.1	90.1	55.7	6.1	337	13.2	49.2	649
	80	2,614	974	108	3.89	5,418	5,028	1,592	1,314	277	1.5	17.4	20	73.6	89.1	90.0	53.1	5.4	287	12.0	49.0	586
	100	2,623	983	108	3.92	5,424	5,034	1,592	1,315	277	1.5	17.4	20	73.6	89.0	90.0	49.8	5.0	251	10.9	49.0	534
3,000	0	3,003	1,201	107	3.46	5,360	4,974	1,592	1,318	273	1.5	17.2	20	73.6	88.8	89.7	26.9	48.9	1,317	26.9	48.9	1,317
	20	2,966	1,219	110	3.77	5,499	5,104	1,592	1,341	250	1.5	15.7	20	73.6	87.3	88.2	49.3	12.6	621	16.2	49.0	791

BESS capacity																						
MWh	t _{H2}	LCOA	Total CapEx	Average annual NH3 production	Average annual NH3 CI	Average annual Haber-Bosch FLH	Average annual Electrolysis FLH	Average annual RES production	Average annual RES consumed	Average annual RES surplus	Grid share total consumption	Curtailment	Average annual Grid consumption	Specific cost of produced RES	Specific cost of consumed RES	Specific cost of consumed RES + Grid	Average annual Nr of Electrolysis Shutdowns	Average Electrolysis Shutdown Duration	Average annual Electrolysis downtime	Average annual Nr of Haber-Bosch Shutdowns	Average Haber-Bosch Shutdown Duration	Average annual Haber-Bosch downtime
		EUR/t _{NH3}	MEUR	kt _{NH3} /pa	gCO ₂ -eq/MJ	FLH	FLH	GWh	GWh	GWh	%	%	GWh	EUR/MWh	EUR/MWh	EUR/MWh	1	hours	hours	1	hours	hours
	40	2,989	1,228	109	3.85	5,473	5,079	1,592	1,331	261	1.5	16.4	21	73.6	88.0	88.9	49.8	8.2	408	12.8	49.0	627
	60	3,010	1,237	109	3.91	5,448	5,056	1,592	1,322	269	1.5	16.9	21	73.6	88.5	89.5	49.1	6.6	323	11.1	49.0	544
	80	3,021	1,247	109	3.93	5,450	5,057	1,592	1,322	270	1.5	17.0	21	73.6	88.6	89.5	47.5	5.8	274	10.1	49.0	495
	100	3,029	1,256	109	3.97	5,452	5,060	1,592	1,322	270	1.5	16.9	21	73.6	88.6	89.5	45.7	5.5	250	9.4	48.9	457
4,000	0	3,324	1,474	111	3.57	5,554	5,154	1,592	1,364	227	1.5	14.3	21	73.6	85.8	86.8	20.8	49.0	1,017	20.8	49.0	1,017
	20	3,338	1,492	111	3.82	5,574	5,174	1,592	1,360	232	1.5	14.6	21	73.6	86.1	87.1	42.7	12.2	521	13.3	49.0	649
	40	3,380	1,501	110	3.90	5,516	5,120	1,592	1,341	250	1.5	15.7	21	73.6	87.3	88.3	44.4	8.3	368	11.0	49.0	536
	60	3,415	1,510	109	3.93	5,473	5,079	1,592	1,328	263	1.5	16.5	21	73.6	88.1	89.1	45.3	6.9	312	10.0	48.9	487
	80	3,427	1,520	109	3.97	5,471	5,078	1,592	1,327	264	1.5	16.6	21	73.6	88.2	89.2	44.3	6.1	269	8.9	48.9	435
	100	3,443	1,529	109	3.98	5,463	5,070	1,592	1,325	267	1.5	16.8	21	73.6	88.4	89.3	43.8	5.8	253	8.5	48.9	416
5,000	0	3,663	1,747	113	3.66	5,670	5,264	1,592	1,392	199	1.5	12.5	21	73.6	84.1	85.1	16.6	49.0	813	16.6	49.0	813
	20	3,716	1,765	112	3.86	5,620	5,216	1,592	1,370	221	1.5	13.9	21	73.6	85.4	86.4	38.9	11.9	463	11.5	49.2	563
	40	3,781	1,774	111	3.92	5,535	5,137	1,592	1,346	246	1.5	15.4	21	73.6	87.0	88.0	41.3	8.6	353	9.9	48.9	482
	60	3,817	1,783	110	3.95	5,496	5,101	1,592	1,334	257	1.5	16.2	21	73.6	87.7	88.7	43.3	6.8	296	8.8	48.9	428
	80	3,836	1,793	110	3.98	5,485	5,090	1,592	1,331	261	1.5	16.4	21	73.6	88.0	88.9	41.6	6.4	268	7.9	48.9	384
	100	3,850	1,802	110	3.99	5,479	5,085	1,592	1,329	263	1.5	16.5	21	73.6	88.1	89.1	41.1	6.0	248	7.4	48.8	359