How to thrive without the grid?

Aligning energy storage with renewables and industrial demand: A techno-economic analysis of local energy systems to electrify the Dutch chemical industry.

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Master thesis

By

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Submitted in partial fulfilment of the requirements for the degree of Master of Science in Management of Technology at Delft University of Technology

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Executive summary

The electrification of the Dutch chemical industry is essential to meet national and European climate targets. However, limited grid capacity and elevated electricity prices currently hinder large-scale adoption. This research investigates the techno-economic feasibility of powering sub-processes at a Dutch chemical plant with a Local Energy System (LES) that integrates Renewable Energy Generation (REG) and Energy Storage Systems (ESS), as an alternative to grid expansion. The objective is to determine the cost-optimal configuration of Short-Duration Energy Storage (SDES) and Long-Duration Energy Storage (LDES) technologies under various system constraints, including capital investment and operational costs, in order to allow an initial trade-off with conventional grid expansion.

This research developed a year-long optimization model using PyPSA to simulate the electrification of a 20 MW thermal process by replacing a natural gas boiler with an electric steam boiler. The model runs on an hourly resolution, incorporating 2024 weather data, a fixed industrial demand, and technical constraints related to storage efficiency, lifetime, and discharge duration. It jointly optimizes the installed power capacities of wind, solar, and two distinct storage types: lithium-LFP batteries (SDES) with up to 6 hours discharge, and iron-air batteries (LDES) with discharge time up to 100 hours.

Three LES scenarios were analysed, each with different storage configurations, and benchmarked against a grid expansion base case. Expert interviews validated the modelling approach, and additional sensitivity analyses were conducted to assess the impact of increased energy demand volatility, constrained REG mix, and SDES capital cost reductions.

The model results show that a LES integrating solar and wind power with iron-air LDES can fully electrify a 20 MW thermal load at competitive cost. The cost-optimal power configuration includes 96.5 MW of wind, 32.3 MW of solar, and 29.3 MW of LDES. This results in total annual system costs of €16.83 million, which is 1.5% lower than grid expansion and 37% lower than an SDES-only configuration.

LDES proved to be the most cost-effective ESS to meet stable chemical demand, due to its low energy-specific cost (€20/kWh) and its ability to buffer multi-day shortages. In contrast, lithium-LFP SDES is limited by its higher energy-specific cost (€182/kWh) and short discharge duration, which does not align with the continuous inflexible energy demand of the chemical industry. This leads to excess REG curtailment and the need for oversized power capacity. In contrast to other studies, hybrid ESS setups offered no additional value under the studied chemical conditions. This underscores that the effectiveness of storage technologies is closely tied to demand profiles and the availability of REG.

Sensitivity analysis showed that SDES becomes cost-effective only under high demand volatility (5–35 MW) or when its CapEx drops by at least 20%. Wind is preferred over solar due to better alignment with continuous chemical demand; solar caused system oversizing and comes with high curtailment. The results underline the importance of aligning ESS design with demand profiles and REG availability.

Expert interviews helped to validate the credibility of the model its technical assumptions but also highlighted practical barriers to LES deployment, including spatial constraints, permitting procedures, and additional system costs. These barriers are expected to impact real-world feasibility. They further noted that the current Dutch policy environment weakens the business case for industrial electrification due to high grid tariffs and limited compensation mechanisms.

In conclusion, this research demonstrates that a cost-competitive LES combining wind, solar, and LDES can fully electrify chemical processes without relying on grid expansion. While technically and economically feasible, real-world implementation will depend on site-specific factors and regulatory reform. The developed model offers a valuable decision-support tool for industries and policymakers aiming to accelerate industrial decarbonisation.

Acknowledgement

Two years ago, I was still working in the field, connecting solar and wind parks to the grid. That experience gave me a first-hand view of both the potential and the limitations of renewable integration. It also convinced me that technical solutions alone would not be enough: the real challenge lies in how technologies are embedded in the larger industrial and societal contexts. This realization encouraged me to pursue the Master's in Management of Technology (MOT) at TU Delft.

This master program challenged me to translate technological opportunities into viable strategies, analysing their economic impact, and embedding them within organizations. The goal was to reflect this approach within my thesis. While rooted in energy systems modelling, my thesis also addresses the broader managerial question of how industry can thrive under grid constraints by adopting emerging technologies. In doing so, I have been able to connect my passion for the energy transition with the tools and perspectives MOT provided me.

Above all, this journey was intense but deeply rewarding. Of course, this contribution was not achieved on my own. A strong committee, each bringing a unique perspective, kept me within the lines, and whenever I became too practical, they pulled me back into the academic amphitheatre. Therefore, I am especially thankful to my supervisory committee.

Aleksandar Giga, your words in the beginning about preparing for a marathon with sprints captured this process perfectly; it was intense, sometimes overwhelming, but ultimately formative. Thanks for our inspiring supervision sessions, I genuinely enjoyed our collaboration.
Linda Kamp, your encouragement combined with constructive criticism gave me the confidence to move forward while keeping a critical eye. I have rarely met someone who replies to emails so quickly, it made the difference.
Na Li, you functioned as the bridge between academia and practice in our discussions, always patient and sharp in pointing out the open ends.

Together, you helped me find the right balance between academic rigor and practical relevance. I sincerely enjoyed working within our team and look back with pleasure and pride.

In addition, I would like to thank the chemical industry experts who participated during the interviews, their practical insights pushed the modelled results to the next level. Finally, I would like to thank Ore Energy for giving me the opportunity to become a part of their team working on their innovative storage solution. It was exciting to witness the company developing at an unprecedented pace.

With the defence of my thesis, I close an important chapter. I am proud to have completed my Master's with a thesis that reflects both my professional background and my academic journey. Now it is my turn to thrive, as I continue my career in the energy transition with the same energy and commitment. At the same time, one of my goals in pursuing this Master's was to experience a student life I had left behind earlier, and I feel I truly did. With a sporadically fanatical rowing crew, the unforgettable experience of organizing the study tour, a lively house with lovely roommates, and all the other wonderful people around me, I have thoroughly enjoyed all the little things in Delft. I learned that during these years, a 12-hour day could somehow stretch into 24, packed with rowing, friends, and countless small moments to enjoy.

Stan Renders,

Delft, August 2025

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List of abbreviations

ACM	Authority for Consumers and Markets (NL)
CapEx	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
DSO	Distribution System Operator
ETS	Emissions Trading System
GHG	Greenhouse Gas Emissions
IKC	Indirect Cost Compensation
LDES	Long Duration Energy Storage
LES	Local Energy System
MABs	Metal-Air Batteries
MDES	Multi-Day Energy Storage
MW / MWh	Megawatt / Megawatt-hour
OpEx	Operational Expenditures
PtH	Power-to-Heat
REG	Renewable Energy Generation
RES	Renewable Energy Sources
SDES	Short Duration Energy Storage
SoC	State of Charge
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TSO	Transmission System Operator
kW / kWh	Kilowatt / Kilowatt-hour

1 Introduction

With rising energy prices, growing grid congestion, and the urgent need to transition to sustainable energy, can the Netherlands remain an attractive location for businesses and industry? The Dutch industry is willing to align with climate targets by electrifying fossil-fuel-based processes. However, grid congestion and elevated electricity prices function as barriers to electrification. With a queue of over 20,000 pending grid connection requests, grid expansion appears unlikely in the near future, highlighting the need for alternative electrical solutions (Koesveld, 2025).

Transitioning the industry from fossil fuels towards sustainable energy increases the dependency of industrial production processes on renewable energy sources (RES), such as wind and solar. However, their intermittency, driven by weather variability and compounded by geopolitical tensions in fossil fuel markets, has resulted in significant energy price fluctuations. Electricity prices for non-household consumers, excluding taxes and levies, increased by 131% between 2021 and 2023 in the Netherlands (Eurostat, 2024). Moreover, natural gas prices doubled or even tripled in the first quarter of 2022 compared to 2021. This surge demonstrates the decisive role of energy prices in the competitiveness of several sectors and regions. The elevated energy prices result in production curtailment and plant shutdowns, ultimately increasing product prices and reducing firms' competitiveness (European Commission et al., 2024).

In response, industries are at a tipping point, exploring alternative energy sources to sustain their operations and competitiveness despite high grid connection tariffs, and elevated electricity prices. Electrification of production processes is widely regarded as one of the most important strategies to achieve climate goals and net-zero emissions by 2050 (Du et al., 2025; Huismans & Voswinkel, 2023; Madeddu et al., 2020). However, meeting Europe's growing energy demand through traditional electrification will require significant grid reinforcement. According to TenneT the current share of electrical energy in the total Dutch energy demand is 20%, but by 2050 it is expected to increase to 40% or 60%. This will require a doubling or tripling of the electricity grid with large implications for infrastructure and society (TenneT, 2024a). This raises concerns about whether electrification and renewable energy adoption can keep pace with industrial needs.

In particular, the Netherlands, as a hub for energy-intensive industries with relatively limited geographical space, faces challenges in expanding its energy infrastructure. Grid congestion limits the growth of industry. Their geographical location often does not allow firms to expand energy consumption, even as they offer to invest in the adoption of solar roofs or local wind turbines (Netbeheer Nederland, 2024). The current situation of the Dutch power grid imposes a barrier to electrification plans which require additional connection capacity (Ministry of Economic Affairs, 2023).

This research addresses these challenges by developing a model using the PyPSA framework to evaluate cost-optimal energy systems for Dutch energy-intensive industries with local generation and energy storage. The model optimizes the installed capacities of intermittent Renewable Energy Generation (REG) and electrical Energy Storage Systems (ESS) to meet a given electricity demand profile. It incorporates the technical characteristics of various ESS technologies, specifically their rated power output [kW] and storage capacity [kWh]. Through scenario-based simulations, the model offers quantitative insights into the trade-offs involved with designing the cost-optimal local energy system (LES), while determining the optimal balance between different ESS. The aim is to offer actionable insights to support Dutch industry in identifying viable alternatives to meet their increasing electrified energy demand.

1.1 Industry specification

This research focuses on a specific segment of Dutch industry, as covering the entire industrial sector would exceed the scope and time of this research. To narrow down the analysis, a targeted selection was made, aiming for the industry with the highest energy intensity. Energy-intensity is an often applied selection criterion, as industries with high levels of energy consumption relative to their value-added production are particularly vulnerable to energy price increases (Bielefeld et al., 2025; Son et al., 2022). Using 2022 data, the Dutch Central Bureau for Statistics calculated the percentage of energy costs relative to added value for each industry. Based on this analysis, the chemical industry is considered the most energy-intensive within the Netherlands, with an intensity of 77.1%. In comparison, the transportation industry, the second most energy-intensive sector, has an energy intensity of only 28.1% (CBS, 2024). This gap underscores the decisive impact of energy prices on profitability in the chemical industry. Small fluctuations in energy prices or supply disruptions can have major cost implications, increasing the pressure to find alternative, more stable energy solutions.

Beyond its economic vulnerability to energy costs, the chemical industry has emerged as a key focus in academic literature on industrial decarbonization. Multiple studies have highlighted its high and continuous energy demand, its reliance on fossil-fuel-based heat, and the significant opportunities for electrification using mature low-carbon technologies (Madeddu et al., 2020; Ouden et al., 2017; Prenzel et al., 2025). This growing academic attention reflects the sector's dual characteristics: high energy-intensity on the one hand, and substantial electrification potential on the other. Given its combination of high energy intensity and strong decarbonization potential, focusing this research on the Dutch chemical sector provides both analytical depth and strong relevance to broader industrial decarbonization and energy transition objectives.

1.2 Literature review

Literature review is performed to map the landscape of decarbonization pathways within the chemical industry and to identify the most mature and promising electrification technologies. Given the complexity and sector-specific maturity of these technologies, a strong literature foundation is essential for defining the scope of this research and to ensure alignment with both academic insights and industrial relevance.

Recent research activity on LES within the chemical industry was identified through a keyword analysis in Scopus, covering the period from 2020 to 2025. To ensure an industry-focused scope, the following keywords were used: *electrification OR "local energy system" AND chemical AND storage AND renewables.* This search yielded 48 relevant articles, which were included in the analysis along with their cited references. The key findings are explained within the remainder of this section and an overview of the key publications is provided Appendix A.

1.2.1 Decarbonization pathways for the chemical industry

A large number of papers is published related to the decarbonization of the chemical industry, they are differentiated by type of (1) decarbonization strategy and (2) energy system scope. The reviewed literature highlights several key approaches to decarbonize: Carbon Capture and Storage/Utilisation (CCS/CCU), direct electrification, and indirect electrification (Madeddu et al., 2020).

CCS refers to the process of capturing CO_2 emissions from fossil-fuel-based processes and storing them in a designated location. While CCS does not decarbonize the underlying chemical production itself, it prevents CO_2 from entering the atmosphere, thereby mitigating its impact on the climate. However, this stored carbon can be applied as feedstock for certain chemicals, referring to the concept of CCU (Baskaran et al., 2024). Neither CCS nor CCU would enable electrification of chemical processes under grid constraints, therefore these technologies are not further considered within this study.

On the other hand, electrification of production processes is widely regarded as a key strategy to reaching climate targets and achieve zero emissions by 2050 (Du et al., 2025; Huismans & Voswinkel, 2023; Madeddu et al., 2020). In literature, electrification is often described using terms such as:

1. Sector coupling,
2. Power-to-X (PtX)
3. Power-to-Heat (PtH)

These approaches can be divided into: (1) direct electrification, where REG is used directly as heat (PtH) or mechanical energy; and (2) indirect electrification, where electricity is converted into e-fuels such as hydrogen or synthetic fuels (PtX). While indirect pathways may help decarbonize existing processes, they tend to have lower overall efficiency and still rely on carbon-based feedstocks (Madeddu et al., 2020). Therefore, this research focuses on direct electrification as the most efficient route to decarbonize chemical production processes.

In the chemical industry, energy consumption is primarily driven by the demand for heat, the generation of high pressures, and separation processes. Unlike sectors that already rely on electrical equipment, chemical plants often depend on fossil fuels to meet these requirements. (Schiffer & Manthiram, 2017). Examples of such equipment are natural gas fuelled steam turbines and naphtha-crackers. Electrifying these processes powered by RES may therefore require modifications to existing infrastructure and technologies at varying Technology Readiness Levels (TRL) (de Pee et al., 2018; Dechany et al., 2023; Smith et al., 2020). The TRL definition is given in Appendix B.

Madeddu et al. (2020) demonstrated that the production of basic chemicals including feedstock accounts for up to 90% of the sectors energy demand and CO_2 emissions in Europe. Figure 1 illustrates how energy demand in the chemical industry is distributed across various energy services Madeddu et al. (2020). A majority of the demand (59%) is associated with medium-temperature heat (100–400 °C), followed by high-temperature heat (400–1000 °C, 13%) and low-temperature heat (<100 °C, 6%). The remaining energy demand is for electricity: 13% for equipment such as motors, compressors, fans, and pumps ("Electric other"), and 9% for space heating and process cooling ("Electric thermal"). This breakdown underscores the leading role of thermal energy in chemical production and highlights where electrification strategies, such as PtH, could be most impactful.

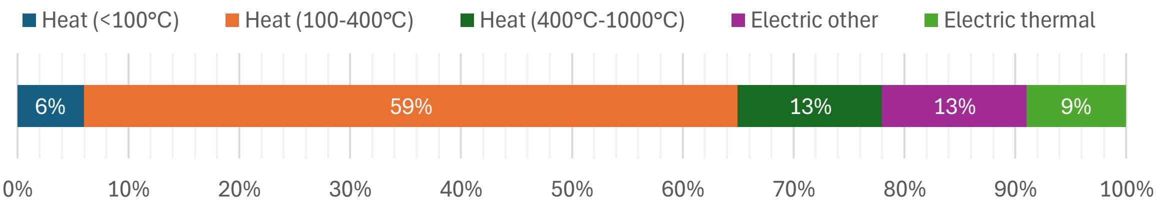

Figure 1: Useful energy demand of European Basic Chemical industry (Madeddu et al., 2020)

While this thermal demand is currently met by fossil-based systems, the growing share of renewable electricity creates new opportunities for electrification (Prenzel et al., 2023). The dominance of thermal energy demand in the chemical industry, as shown in Figure 1, underlines the relevance of direct electrification strategies such as PtH, which converts electricity directly into usable thermal energy. PtH stands out as a mature, efficient, and retrofittable technology for supplying process heat with renewable electricity, making it a key pathway for decarbonizing chemical production processes (Prenzel et al., 2023). Given its technological maturity, system efficiency, and ease of integration into existing operations, this study adopts PtH as the primary electrification strategy.

Figure 2 builds on this by linking the most promising PtH technologies to their specific temperature range and comparing them to the conventional natural gas boiler. Each PtH-technology is designed to replace a fossil-fuel-based component as an electrified alternative, many of which can be retrofitted into existing infrastructure. The TRL of these solutions generally correlates with their operating temperature, with lower-temperature applications often being more mature (de Bruyn et al., 2020).

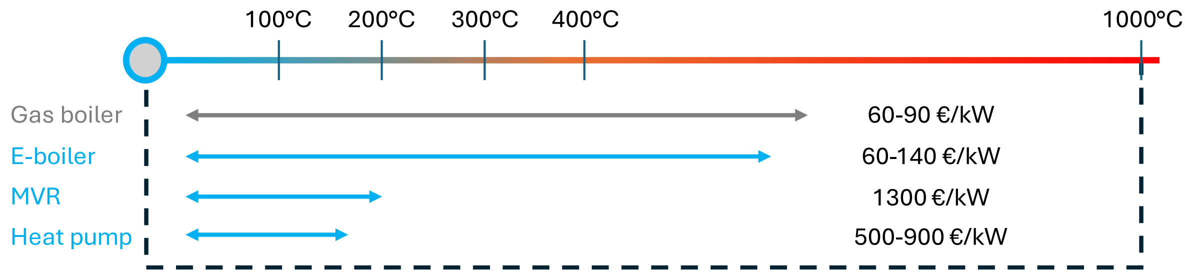

Figure 2: Operation temperatures of promising electrification technologies (Madeddu et al., 2020; Ouden et al., 2017).

Heat pumps are currently commercially available for low-temperature processes (<100°C) with thermal output up to 20 MW. However, for higher-temperature applications (up to 165°C) the reported maximum capacity drops to around 660 kW (Madeddu et al., 2020). While high-temperature heat pumps have promising efficiencies for industrial electrification, their limited TRL and small temperature range, remain barriers to large-scale (MW) deployment. Mechanical Vapour Recompression (MVR) and steam recompression offer more mature alternatives, as these technologies are already commercially available and proven. Nevertheless, both MVR and heat pump systems require further technological development and reductions in capital expenditure (CapEx), and in some cases operating expenditure (OpEx), to be economically viable for widespread industrial adoption.

Among the available technologies, the electric steam boiler (e-boiler) most closely matches the operating characteristics of conventional gas-fired boilers. With a TRL of 9, e-boilers are commercially available at capacities of up to 90 MW and can operate at temperatures up to 600°C and pressures of up to 150 bar, achieving efficiencies close to 99% (Ouden et al., 2017). Despite their maturity, large-scale deployment is hindered by high grid connection costs, capacity tariffs, and elevated electricity prices throughout most of the year, especially in grid-congested regions (Madeddu et al., 2020). These challenges underscore the importance of a LES which combines REG and ESS to reduce reliance on the external grid, and mitigate rising energy prices, which is the central focus of this research.

1.2.2 Available Energy Storage Systems (ESS)

ESS are a critical component of LES, as they enable the balancing of intermittent REG. To ensure this research is firmly embedded within the existing literature, a comprehensive understanding of the different ESS types was essential. A study performed by (Farivar et al., 2023) discussed the notion of ESS in a broad context. Therefore, they distinguish 5 types of ESS:

1. Mechanical (Flywheels; Pumped Hydro; Compressed Air)
2. Thermal (Sensible heat; Thermochemical; Latent Heat) (Alva et al., 2018)
3. Electrical (Supercapacitors; SMES)
4. Electrochemical (BESS-Lithium; Flow batteries)
5. Chemical (Hydrogen, Ammonia, Methanol)

All ESS types run through a cycle of charge and discharge when operational. However, they vary at the speed in which they are able to run the cycle, making them suitable for different applications. Figure 3 illustrates how ESS can be categorized based on two parameters: storage capacity [kWh] and power [kW]. The capacity of an ESS is the amount of energy it can store [kWh], whereas the power is the maximum rate at which it can release this energy [kW] (Cole et al., 2021). The ratio between the ESS capacity [kWh] and maximum power [kW] is called the discharge time [h] or the energy-power ratio, referring to the time it takes for the ESS to discharge from 100% to 0%, with maximum power output.

This relationship is defined mathematically in Equation 1. Short-Duration Energy Storage (SDES) has a short cycle with a low energy-power ratio and short discharge time, making it suitable for peak shifting. Peak shifting refers to charging SDES during periods of low electricity demand or excess REG and discharging during peak demand hours to alleviate stress on the grid or reduce peak tariffs. In contrast, Long-Duration Energy Storage (LDES) has a long cycle with a high energy-power ratio, and larger discharge times, making this system type more efficient for base load demand (López-Ceballos et al., 2025). Even fossil fuel could be considered as (chemical) ESS, and society is currently discharging them at an irreversible rate by burning those fossil fuels rapidly (Farivar et al., 2023).

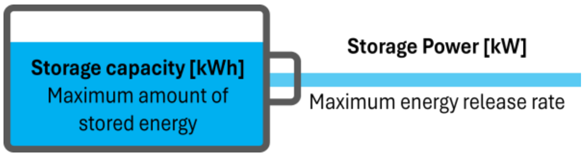

Figure 3: Visualisation of Power [kW] and Capacity [kWh]

$$Discharge\ time\ [h] = \frac{\text{Capacity [kWh]}}{Power\ [kW]}$$

Equation 1: Ratio between capacity [kWh] and Power [kW]

Du et al., (2025) provides an interpretation of ESS in chemical applications, proposing a versatile approach to assess a long-term energy system capable of decarbonizing a chemical production site. Their study distinguishes itself from other papers like (Allman & Daoutidis, 2018; Li et al., 2020) by considering not only the intermittency of REG in a short period, (daily or weekly) but also on a year-round basis. The paper concludes that the influence of seasonal variation of solar- and wind energy production causes power variation that requires a 40 – 100 times larger Battery Energy Storage System (BESS) size compared to daily fluctuations in power (Du et al., 2025). This is supported by the findings of Wang et al., (2020), who conducted a comparable study on the electrification of ammonia production using lithium-based BESS in combination with wind energy. Their results show that the SDES was used primarily to shift energy over a 48-hour period, which exceeds the typical discharge duration of lithium-based SDES; usually 4 hours or less (Denholm et al., 2023). This mismatch can lead to oversizing; Using an SDES battery for long-duration applications requires oversizing its power capacity (kW) to extend the discharge duration. Conversely, using an LDES for short-duration needs leads to excessive energy capacity (kWh) to meet the required power output, making the system inefficient and unnecessarily costly.

Multiple studies highlight the need for more advanced ESS solutions (C. Chen & Yang, 2021; Du et al., 2025; López-Ceballos et al., 2025; Wang et al., 2020), ideally combining the strengths of SDES and LDES: (1) the high efficiency and low power costs [€/kW] of SDES, optimized for peak demand, (2) the low energy capacity cost [€/kWh] of LDES, suited for long-duration baseload supply (López-Ceballos et al., 2025). A deeper explanation of the promising ESS technologies is given in section 2.3.

1.2.3 Renewable energy generation

Renewable energy is generated directly from natural sources that replenish themselves faster than they are consumed (United Nations, n.d.). The most mature renewable energy technologies are solar and wind energy. Solar energy can supply heat, light, electricity, and fuels for various applications. Electricity generation from solar radiation is typically achieved either through photovoltaic (PV) cells or by using mirrors in concentrated solar power (CSP) plants. Because CSP needs high direct irradiance, PV is more suitable for the Dutch climate (Alva et al., 2018). Wind energy, on the other hand, captures the kinetic energy of moving air and converts it into mechanical or electrical power. Wind turbines can be installed onshore, supporting decentralized REG, or offshore, where wind speeds are typically higher and more stable, resulting in more efficient use of the installed capacity. In 2023, wind energy accounted for approximately 24% of total REG in the Netherlands, while solar contributed 16.5% (IEA, 2025). Based on these findings solar PV and Wind turbines are the considered RES in this research.

1.2.4 Literature gap

Replacing fossil fuels with low-carbon electricity in chemical production processes is widely regarded as a key strategy for meeting climate goals (Du et al., 2025; Huismans & Voswinkel, 2023). As a result, an increasing number of studies have explored the potential of electrified chemical production, establishing a broad foundation of different electrification pathways (Chen & Yang, 2021; Dechany et al., 2023; Du et al., 2025; Prenzel et al., 2025; Wang et al., 2020). One prominent example is PtH, which converts electricity into heat for such usage as steam in chemical processes (Madeddu et al., 2020).

However, to effectively reduce the carbon footprint of electricity used for heat production, coupling PtH with REG, such as solar and wind, is essential. This can be facilitated through Power Purchase Agreements (PPAs) which are long-term contracts in which a buyer agrees to purchase electricity directly from a producer at a fixed price (Prenzel et al., 2025). Despite its potential, the high cost of electricity and limited grid capacity to transport the electricity to the chemical sites remain major barriers to PtH implementation (Madeddu et al., 2020). While deployment of LES in which REG is combined with ESS could reduce grid dependency and mitigate energy price increases, studies investigating such integrated solutions within the Dutch chemical industry are notably lacking. This results in a knowledge gap within the chemical industry possibly causing uninformed energy system design choices, which could ultimately result in economic migration of the Dutch industry.

Additionally, due to the variable nature of solar and wind power (explained later in section 2.1), ESS solutions must be capable of storing electricity over multiple durations. For example, López-Ceballos et al., (2025) highlighted that hybrid ESS systems combining SDES and LDES can provide cost advantages over single-technology systems in the built environment. However, this insight has not yet been sufficiently explored within the context of the chemical industry, particularly in the Netherlands. The specific characteristics of chemical production, with continuous high energy demand, and process stability requirements, differ substantially from those in the built environment. The lack of studies assessing hybrid ESS configurations within chemical settings reveals a clear gap in the existing body of knowledge. As a result, the potential role of hybrid ESS in enabling reliable and cost-effective electrification of chemical processes remains insufficiently understood.

This study addresses this gap by evaluating two fundamentally different ESS: SDES systems such as lithium-LFP batteries, which are optimized for high power and short discharge times (<6 h), and LDES systems such as iron-air batteries, which offer low energy-specific costs and long discharge durations (>100 h). While both technologies have been studied individually, their combined use in a hybrid configuration remains unexplored in the context of continuous industrial demand and grid constraints. This research therefore provides new insights into the effectiveness of hybrid ESS systems (combined SDES-LDES) for reliable and cost-effective electrification in the Dutch chemical industry.

1.2.5 Academic contributions of this study

This research provides a threefold contribution to the existing academic literature:

Quantifying the cost-effectiveness of hybrid SDES-LDES systems: By incorporating technical constraints related to both SDES and LDES, the developed model enables a meaningful comparison of their applicability within the chemical industry. This study evaluates the potential cost advantages of hybrid SDES–LDES configurations over single-technology systems, contributing to a better understanding of the typical roles and performance characteristics of SDES and LDES when deployed as large-scale ESS in energy-intensive industries with high and continuous electricity demand.

Incorporating seasonal weather variability in energy storage design: The optimization model developed in this research extends beyond conventional hourly or daily analyses by considering system performance on a year-round basis. This allows for the inclusion of seasonal variability in solar and wind energy generation, a factor that has been identified as significant for SDES-only systems (Du et al., 2025), but remains underexplored in hybrid ESS configurations. By linking seasonal REG variability to the optimal sizing and combination of multiple ESS technologies, the model supports the development of more resilient and informed energy system designs for chemical applications.

Understanding of key design drivers for ESS configuration: Through scenario- and sensitivity analysis, involving different combinations of installed RES and variations in technological constraints of ESS, this study identifies the most influential factors affecting the sizing of SDES and LDES capacities. This insight helps to clarify which technical or economic constraints most strongly shape LES design and can inform future research and policy development in the context of industrial decarbonization.

1.3 Research objective & questions

The electrification of industrial energy consumers requires grid expansion which cannot keep up with the pace of industrial needs (Ministry of Economic Affairs, 2023). This could cause economic migration of industrial players to countries where they can expand their business operations. To keep the Netherlands an attractive country for businesses to locate themselves, it is important to inform the industry about their alternatives for energy supply. Therefore, this research aims to develop techno-economic analysis for Dutch chemical companies to electrify parts of their existing chemical processes without increasing their reliance on the central grid. By minimizing reliance on the central grid, this research aims for a strategy to prevent grid-congestion-driven limitations on business growth and mitigate elevated electricity prices reducing profitability.

This study develops a techno-economic optimization model together with a thesis report as main deliverable to evaluate the cost-optimal LES configuration. The model enables the integration of the technical characteristics of SDES and LDES technologies into a hybrid ESS and minimizes total system costs by jointly optimizing installed capacities for REG and both types of ESS.

In this context, "optimal" refers to the minimized total-system-cost configuration that enables continuous and reliable operation of electrified chemical production. The total system costs include annualized capital expenditures (CapEx) for REG and ESS (SDES & LDES), as well as operational expenditures (OpEx) such as maintenance and electricity imports. By integrating technical constraints, cost structures, and deployment scenarios, this research addresses the knowledge gap regarding the effective dimensioning of hybrid ESS systems for chemical decarbonization. It provides actionable insights to support decision-making around ESS deployment strategies in the Dutch chemical sector.

The main research question within this research is as follows:
"How do different energy storage duration and renewable generation configurations affect the cost-effectiveness of local energy systems to electrify a Dutch chemical plant facing grid congestion?"

This main question evaluates the feasibility of transitioning a chemical plant's fossil-fuel-based production process to an electrified local energy system with different ESS configurations. Grid congestion and high energy prices pose significant barriers to such electrification efforts. Local REG, in combination with ESS, could offer a viable solution by reducing dependency on the external electricity grid.

The main research question will be addressed by answering the following sub-questions:

1. Which chemical processes are considered electrifiable according to current academic literature?
This question will be answered based on literature review. It explores the potential of electrification of the existing chemical processes and identifies which processes are the most promising to electrify.

2. **What storage systems are available to fulfil the energy demand of electrifiable chemical processes according to academic literature?**

Literature review identified the possible ESS technologies and possible combinations. This question describes the different possibilities of energy storage systems on which the model in the end will optimize based on the input parameters.

3. **Which evaluation criteria are relevant for comparing Energy Storage Systems technologies in chemical applications?**

This question identifies the key evaluation criteria for comparing energy storage technologies in chemical industry applications. The criteria informed the model design and helped to assess the suitability of SDES and LDES under different operational conditions.

4. **What is the cost-optimal combination of SDES and LDES to meet a chemical plant's energy demand?**

Using the optimization model, different ESS configurations are evaluated against a fixed demand profile and REG availability.

5. **How do SDES and LDES compare in their techno-economic performance for electrified chemical processes?**

The pros and cons of SDES and LDES storage are discussed for the electrification of chemical processes. Scenario analysis is used to explore trade-offs and synergies between SDES and LDES technologies.

1.4 Reading guideline

This thesis is structured to guide the reader from context and theoretical foundation toward technical analysis and practical insights. Chapter: 1 introduces the problem context, research gap, and research questions. Chapter: 2 elaborates on the characteristics of SDES and LDES combined with their relevance in managing renewable energy variability. Chapter: 3 outlines the research approach, including the PyPSA modelling framework, case study selection, and validation approach. Chapter: 4 presents the results of three scenario analyses, informing the most cost-effective LES configuration. Thereafter, Chapter: 5 explores the sensitivity of the outcomes to key assumptions, while Chapter: 6 provides a qualitative validation of the model outcomes through expert interviews with industry stakeholders. Chapter: 7 discusses key findings, including the limitations of the model and implications for policy. Finally, chapter: 8 answers the research questions and offers recommendations for future work. The appendices contain supporting data, modelling assumptions, and additional visualizations.

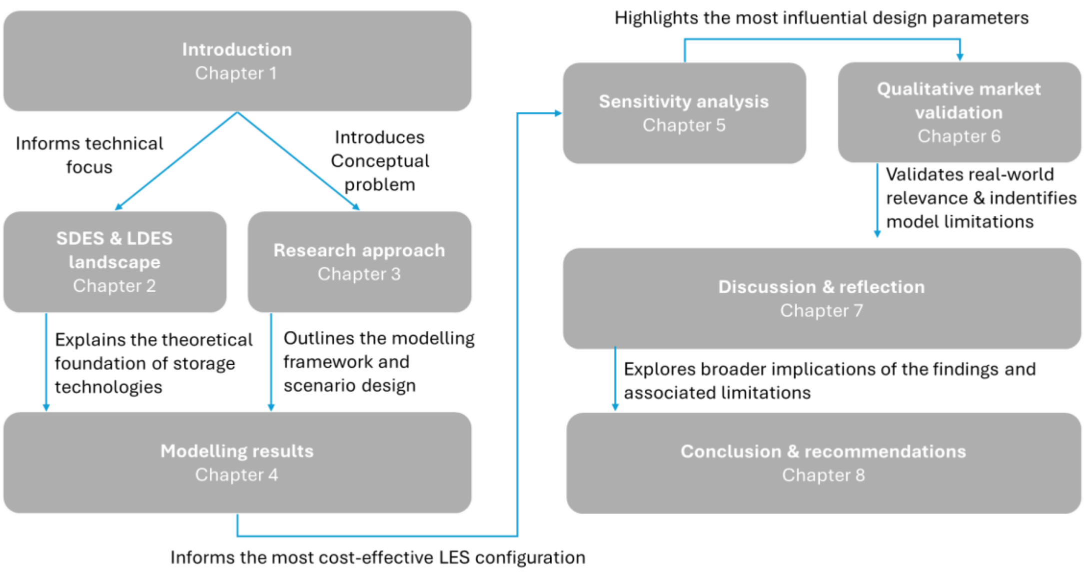

Figure 4: Visualisation of interrelationships between chapters

2 SDES and LDES landscape

This chapter builds on the explanation of ESS provided in section 1.2.2 and links key technologies to each ESS duration category. The need for both SDES and LDES is justified based on the varying patterns of REG intermittency of solar and wind. The chapter gives an overview of SDES and LDES characteristics and identifies one promising technology per category to be used as input for the optimization model discussed in section 3.2. This chapter concludes with the recent Dutch energy market dynamics and how it relates to ESS.

2.1 Variable renewable energy intermittency

The Dutch electricity grid is becoming increasingly saturated with REG mostly from solar and wind. The frequency of the intermittency from both RES appears to be different and is directly related to weather circumstances. Figure 5 shows the relative power output of different RES as a fraction of its maximum installed power capacity (kW) for a period of 12 days in the Netherlands in 2024. The plot is created using the PyPSA framework (Brown et al., 2018), which allows for illustrating the locally available REG potential based on historical weather data (Pfenninger & Staffell, 2016). A clear observation of the figure below is the different power outputs for different REG technologies. Typically, solar technology (yellow hatch) exhibits a clear daily pattern with intra-day cycles, which is easily explained by the Earth's rotation. On the other hand, wind turbine technology (blue hatch) tends to be less volatile with multi-day fluctuations and longer periods with less power generation.

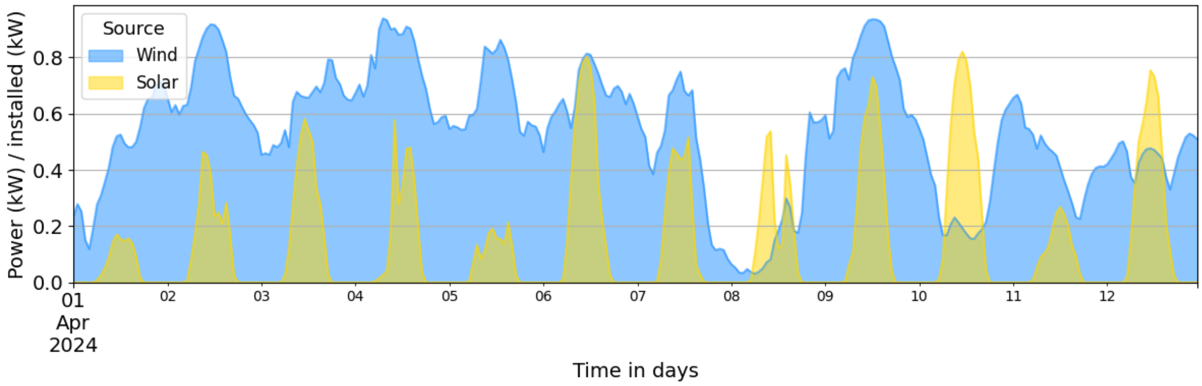

Figure 5: Relative electricity generation profiles from different RES systems as a fraction of its maximum capacity.

For Dutch chemical plants facing grid congestion, the electrification of production processes increasingly depends on the viability of LES. However, while REG with on-site solar and wind installations can bypass the need for additional grid capacity, their intermittent nature introduces a new set of challenges. Ideally, the electricity demand of the chemical plant would fluctuate together with wind power and solar radiance or vice versa. However, given the need for stable and reliable energy to ensure profitability in this energy intensive industry (Chemelot, 2024), and the fact that weather conditions cannot be controlled, flexibility-providing assets are critical to prevent curtailment, either in REG or industrial production. In a system with large shares of REG and a continuous electrical demand ESS is essential to prevent supply shortages during dark wind shortages. Periods of high REG (on a windy & sunny day) could exceed on-site demand, leading to REG curtailment and under-utilized infrastructure. Conversely, during dark wind shortages, REG may fall short, forcing the acquisition of expensive peak electricity from the grid or even chemical process curtailments.

To avoid such inefficiencies, the LES must be able to store surplus REG and discharge it when REG drops while demand remains. Without ESS, the energy infrastructure must be over-dimensioned to secure energy supply during dark wind shortages, undermining the economic case for LES. Energy storage technologies provide a critical solution by enabling temporal decoupling between REG and process consumption. As, they allow surplus renewable electricity to be stored and discharged during periods of low REG, minimizing both curtailment and reliance on the central grid.

However, selecting the appropriate ESS type based on discharge duration (SDES or LDES) is essential for cost-effective system design. Figure 5 illustrates how the REG frequencies of solar and wind differ substantially, highlighting the need to align ESS discharge durations with the specific characteristics of the chosen REG configuration. This is further clarified with Figure 6, which shows a frequency analysis on the entire REG dataset to understand the possible benefits of combined ESS to design a cost-effective LES. To inform this decision, the frequency analysis is conducted on the output of wind and solar generation over time. The resulting spectrum, shown in Figure 6, reveals the dominant fluctuation patterns in each technology. The yellow peak near 1.0 cycles per day reflects the strong daily pattern of solar energy generation, which is directly linked to the day-night cycle. In contrast, wind energy (blue) exhibits a flatter spectrum with greater amplitude at lower frequencies (below 0.5 cycles/day), indicating stronger multi-day to seasonal variability. These slower dynamics justify the need for LDES to maintain supply continuity during extended periods of low wind. Similar results on the generation profiles of solar and wind were generated in a comparable study on a different case from Clerjon & Perdu (2019).

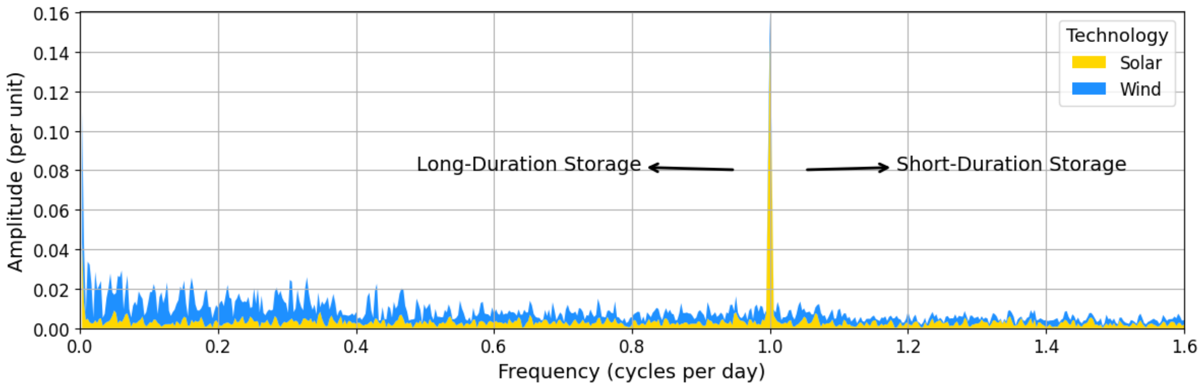

Figure 6: Frequency spectrum of normalized solar and wind generation in the Netherlands (2024).

This frequency analysis forms the foundation for ESS configurations within the techno-economic model. With the alignment of ESS duration and REG profiles, chemical plants can optimise the economic return on LES investments. Ensuring reliable, low-carbon electrification while minimizing grid dependency. Emphasizing the need for further research on the added value of including both SDES and LDES within an optimal energy system. Therefore, this research aims to identify the influence of the REG portfolio on ESS sizing with combined SDES and LDES technologies.

2.2 Short-Duration Energy Storage technologies

This section provides an overview of key ESS applicable to SDES. Based on literature it highlights their main advantages and limitations, followed by the selection of the most suitable technology for implementation in LES on chemical production sites.

SDES systems are designed to absorb and release electricity over short timeframes, typically ranging from a few minutes up to four to six hours (IRENA, 2024). A formal definition of the storage duration for SDES is not provided in the literature; however, values typically range up to six and ten hours of discharge time across different technologies (Guerra, 2021; IRENA, 2024). SDES technologies play a crucial role in stabilizing power systems with high shares of variable renewable energy by enabling services such as peak shaving, frequency regulation, and short-term load shifting. Key SDES technologies together with their main advantages and disadvantages reviewed in literature are listed in Table 1.

Table 1: Overview of key SDES technologies, including their main advantages and disadvantages, based on insights from the following sources: [1](H. Chen et al., 2009) [2](Ikeuba et al., 2024) [3](IRENA, 2024) [4](Schmidt & Staffell, 2023) [5](Viswanathan et al., 2022) [6](Woodford et al., 2022) [7](Clerjon & Perdu, 2019)

Technology	Positive Aspects	Negative Aspects
Lead-Acid	+ Low cost[7] + Mature technology[1] + High recyclability[5]	– Low energy density [1] – Limited cycle life [7] – Toxic materials [5,7]
Lithium-ion (LFP)	+ High energy density[3,4] + High round-trip efficiency[3,4] + Fast response time[3,4] + Significant cost reductions[3,4]	– Resource criticality (Li, Co)[4] – Recycling challenge[5] – Still relatively costly[4] – Limited cycle life[4]
NaS (Sodium–Sulfur)	+ High energy density[5] + Long cycle life[5] + Utility-scale proven[1]	– High-temp operation (~300°C)[1] – Thermal risk[5] – High CAPEX[5]
NiCd	+ Temperature robust[5] + Long cycle life[5]	– Highly toxic cadmium[1] – Obsolete[1]
NiMH	+ Safer than NiCd[1] + Higher energy density than NiCd[2]	– Lower energy density than Li-ion[1] – High self-discharge[2] – Relatively costly[1]

Among the key technologies available, lithium-ion (LFP) batteries have emerged as the preferred choice for SDES, particularly for applications requiring four hours or less of discharge (Denholm et al., 2023). This preference is attributed to their combination of high round-trip efficiency (up to 95%), high energy and power density, fast response times, and modular scalability (IRENA, 2024).

Since 2021, lithium iron phosphate (LFP), a subtype of lithium-ion, has accounted for the majority of new stationary storage deployments, reaching 84% of global market share in GWh terms by 2023 (IRENA, 2024). Focusing on the Netherlands, according to Global Energy Storage Database provided by Nguyen & Tamrakar (2024), a total of 23 ESS are connected to the Dutch grid. The vast majority of these systems have a discharge time of two hours or less (SDES) with rated power ranging between 50 kW and 10,000 kW, almost exclusively lithium-ion technology.

From a cost perspective, lithium-LFP battery systems have experienced a significant 82% reduction in installed costs between 2010 and 2023 (IRENA, 2024). Economies of scale are expected to further reduce costs, solidifying their role in the energy transition. Despite competition from emerging chemistries aimed at LDES, lithium-ion is projected to maintain its leading position in SDES markets through 2030 and beyond (IRENA, 2024; Schmidt & Staffell, 2023). Therefore, the remainder of this research will focus on lithium-LFP as the most promising SDES technology.

2.3 Long-Duration Energy Storage technologies

In contrast to SDES, LDES technologies are designed to deliver energy over discharge durations exceeding 10 hours (Guerra, 2021). While lithium-LFP batteries dominate the SDES landscape, their applicability for durations beyond 4–6 hours is limited due to increasing technical and economic challenges. Particularly the high cost of scaling energy capacity [€/kWh], which stems from the reliance on scarce and expensive raw materials such as lithium, cobalt, and nickel (Denholm et al., 2023).

This section begins by outlining the most widely discussed LDES technologies (hydrogen, thermal energy storage, and metal-air batteries) after which the most promising options are compared to ultimately identify the most promising LDES technology which will be included in the model.

Hydrogen (H_2) | H_2 can be used to decarbonize industry both as a feedstock for further chemical production and as an ESS to supply energy during dark wind lulls (PtX) (Dechany et al., 2023). When H_2 is considered as ESS, the study by C. Chen & Yang (2021) highlights its potential role for supporting renewable energy integration. However, its large-scale application remains challenging due to big technical barriers, including high storage costs and the need for high-pressure conditions to achieve efficient storage, which also introduces potential safety risks. Furthermore, Prenzel et al., (2023) highlight that although green hydrogen could serve as a potential fuel for cogeneration, the future developments of its pricing and low production efficiency make it less effective than direct electrification routes. The reviewed literature emphasises the urgent need to explore new technologies and concepts for ESS since those barriers make H_2 less favourable for long-term storage (C. Chen & Yang, 2021; Prenzel et al., 2023).

Thermal Energy Storage (TES) | Secondly, the reviewed literature identifies Thermal Energy Storage (TES) as a promising technology to support the decarbonization of the chemical industry. Alva et al. (2018) provides a comprehensive overview of TES technologies, which can be classified into three categories differentiated by the material used for storage. Among these, sensible heat TES stands out as the most suitable option for electrifying the high energy demand of chemical plants (Alva et al., 2018). Sensible heat TES materials such as; water, oil, and salt, store energy via their specific heat capacity (Cp), and are currently at the highest TRL (8–9) (Alva et al., 2018). These materials are often inexpensive, widely available, non-toxic, and non-flammable. While latent and chemical TES also show potential for future applications, both require further development and are not yet viable for electrifying existing Dutch chemical plants today. Klasing et al. (2018) further examined three sensible TES technologies who are the most relevant to the chemical sector, highlighting molten salt as a particularly effective option. This sensible, indirect TES can operate between 170°C and 560°C and is commonly used in concentrated solar power plants (Alva et al., 2018). Prenzel et al. (2025) further confirmed the value of Molten Salt TES through an optimization model for zero-emission chemical sites, showing that implementing molten salt storage can reduce system costs by up to 27%. TES enables the efficient use of intermittent renewable sources like solar and wind, while also improving resilience against green hydrogen price volatility. However concerns are mostly related to the self-discharge and efficiency of TES being well under 50% making them not very suitable for applications where renewable energy is not in excessive presence (Alva et al., 2018).

Metal-Air Batteries (MAB) | Lastly, among ESS, electrochemical Metal-Air Batteries (MAB) are receiving attention due to their promising characteristics. MAB generate electricity via an electrochemical reaction in which a metal, such as iron or zinc, is oxidized at the anode while oxygen from the air is reduced at the cathode. MAB can utilize inexpensive and abundant metals (e.g., Zn, Fe, Al) and offer high theoretical energy densities that may outperform conventional lithium-ion batteries (Bogomolov & Ein-Eli, 2025). These features make MAB strong candidates for low-cost, long-duration energy storage (López-Ceballos et al., 2025).

In particular, iron-air batteries are considered safe, scalable, long-lasting, and economically promising for large-scale ESS applications (Bogomolov & Ein-Eli, 2025; Ikeuba et al., 2024). Currently, iron-air batteries are still at the development phase (TRL 4-5); however, they are the closest to surpassing the required thresholds for cost and energy density for grid-scale applications (Bogomolov & Ein-Eli, 2025). Despite this theoretical potential, studies specifically addressing the integration and performance of iron-air batteries within industrial sectors remains scarce.

A key limitation of MAB is their relatively low round-trip efficiency (~50%), compared to 85% or more for lithium-ion batteries (Denholm et al., 2023). This trade-off makes iron-air batteries less suited for applications requiring frequent charge-discharge cycles, because frequent cycles will result in higher energy losses, limiting their suitability for SDES. Nonetheless, their ability to store large amounts of energy cost-effectively over multi-day periods makes them well-suited for balancing prolonged mismatches between renewable supply and industrial demand. As such, iron-air MAB could potentially complement SDES within a LES to improve system reliability and reduce REG curtailment in future energy systems.

The most promising electrochemical LDES alternatives, as outlined in Table 2, are characterized by using abundant and low-cost materials, making scaling in terms of energy capacity [kWh] relatively cheap (Bogomolov & Ein-Eli, 2025). Literature highlights MAB and redox flow batteries technologies as leading solutions for LDES, due to their scalability and material sustainability. An overview of the main positive and negative aspects among the promising technologies is given in Table 2.

Table 2: Overview of key LDES technologies, including their main advantages and disadvantages, based on insights from the following sources: [1](H. Chen et al., 2009) [2](Ikeuba et al., 2024) [3](Viswanathan et al., 2022) [4](Woodford et al., 2022)

Technology	Positive Aspects	Negative Aspects
Zinc–Air (MAB)	+ High energy density[2]	− Rechargeability barrier[2]
	+ Low-cost, abundant[3]	− Short cycle life[3]
Iron–Air (MAB)	+ Low chemical cost[4]	− Low efficiency[4]
	+ Non-toxic and scalable[4]	− Low power density[4]
	+ Abundant iron utilization[4]	− Emerging tech[4]
Lithium-Air (MAB)	+ Very high energy density[2]	− Low TRL[2]
	+ 5–10× Li-ion energy capacity[2]	− Rechargeability issues[2]
	+ Lightweight[2]	− O_2 management required[2]
Redox Flow Batteries (e.g. Vanadium)	+ Energy/power decoupling[3]	− Low energy density[3]
	+ >10,000 cycles[3]	− High CAPEX[3]
	+ Relatively safe[1]	− Complex system[3]

Redox Flow Batteries, though commercially mature and operationally safe, suffer from low energy density, high system complexity, and costly membranes that constrain their economic competitiveness (Bogomolov & Ein-Eli, 2025). A cost threshold analysis by Bogomolov & Ein-Eli (2025) concluded that no commercially available battery technology could yet meet the requirements for grid-scale energy storage. However, MAB, especially zinc-air and iron-air batteries were identified as the most promising technologies to surpass the cost and energy density thresholds. Zinc-air and iron-air offer high theoretical energy densities and sustainability but face limitations related to rechargeability and low roundtrip efficiency (Ikeuba et al., 2024; Woodford et al., 2022). Lithium-air batteries offer exceptionally high energy density but remain constrained by poor rechargeability and oxygen management complexity (Bogomolov & Ein-Eli, 2025).

Overall, power capacity cost [€/kW] and discharge efficiency remain critical drivers in determining the cost-effectiveness of LDES technologies (Guerra, 2021). Among these, iron-air batteries have emerged as an environmentally friendly option, combining material abundance (iron and oxygen) with projected energy costs as low as €20/kWh, and an estimated roundtrip efficiency of approximately 45% (FormEnergy, 2023; Ikeuba et al., 2024). Iron-air batteries are further characterized by a high energy-to-power ratio, resulting in low power density, which limits their ability to quickly deliver energy during short-term demand peaks. This limitation stems from inherently slow electrochemical reaction kinetics, which constrain the rate of energy conversion during discharge. Combining these technical benefits with their promising cost trajectory, this research selects iron-air as the most promising LDES technology for further analysis.

2.4 Key characteristics comparison

A targeted literature review is performed on lithium-LFP (as representative of SDES) and iron-air (as representative of LDES), focusing on their total project investment cost structures. To meaningfully compare these ESS, a distinction is made between energy capacity investment costs [€/kWh] and power-specific investment costs [€/kW]. This distinction is essential because SDES and LDES exhibit different discharge durations, which are directly related to their energy-to-power ratio [kWh/kW].

LDES technologies like iron-air are designed to supply energy over long durations, typically exceeding 100 hours (FormEnergy, 2023). They feature a high energy-to-power ratio, as their storage medium is relatively inexpensive (€20/kWh) allowing for large energy capacities at low €/kWh. However, the systems required to convert stored energy into power are cost-intensive, resulting in high €/kW values.

In contrast, SDES technologies such as lithium-LFP are optimized for 1-6 hours discharge. Lithium cells can deliver high power per unit but have limited energy capacity, resulting in low energy-to-power ratios and relatively high €/kWh. Consequently, SDES is more suitable for frequent cycling applications.

These conceptual differences in cost structure and discharge duration between SDES and LDES are reflected in the total project investment costs presented in Figure 7. The figure enables the comparison of the capacity-specific [€/kWh], and power-specific [€/kW] investment costs for the representative ESS, as reported by various literature sources.

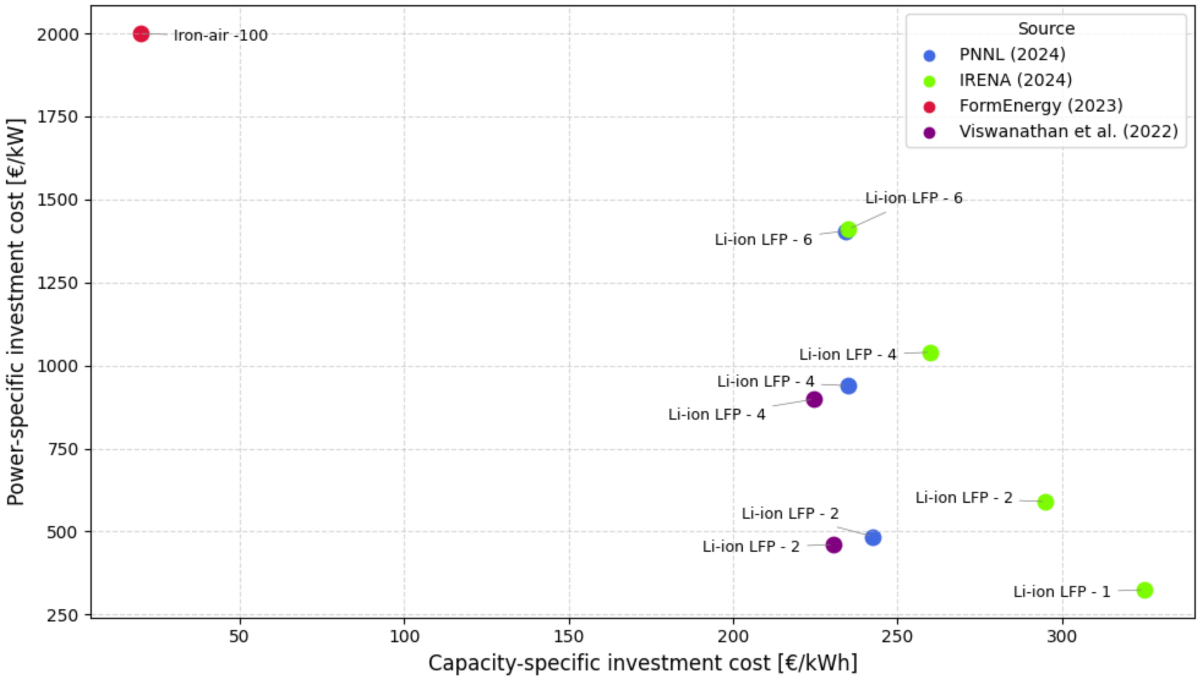

Figure 7: Total project Investment cost comparison ESS technologies. (FormEnergy, 2023; IRENA, 2024; PNNL, 2024; Viswanathan et al., 2022)

Figure 7 illustrates how the iron-air system (LDES) achieves low energy capacity cost (€20/kWh) but at very high power cost (€2,000/kW), while lithium-LFP systems (SDES) cluster around higher capacity costs (€235–325/kWh) but significantly lower power costs, with values between €325/kW for 1 hour applications and €1,410/kW for 6 hour applications. In short, the power-specific costs [€/kW] increase linearly with storage duration because delivering the same power [kW] over a longer period requires more energy capacity [kWh]. Effectively, longer duration storage requires more cells, leading to higher system costs per kW and making the need for a low-cost cell increasingly important. This reflects the fundamental trade-off between energy capacity and power delivery, highlighting the importance of aligning the SDES and LDES configuration with REG and demand to achieve a cost-optimal energy system.

2.5 Market dynamics

This section illustrates how emerging pricing structures in the Dutch electricity market increasingly incentivize demand-side flexibility. A shift that reinforces the relevance of ESS as a potential solution for enabling such flexibility in energy-intensive chemical settings, alongside with its potential to address rising energy costs and grid constraints. It introduces three key national energy challenges:

1. Meeting international commitments to reduce CO_2 emissions (Kukharets et al., 2023).
2. Decreasing energy dependence on politically unstable or unreliable regions.
3. Maintaining the affordability of energy for both households and the industrial sector.

These challenges put pressure on the Dutch economy. The country hosts around 3,800 business parks, most of which are located in grid-congested areas (Anaïs, 2024). Grid congestion increasingly forces companies which are eager to thrive to choose between investing in local alternatives or relocating to regions with more available grid capacity. As a result, electrification plans such as replacing fossil-based heat with electricity are at risk. Recent studies estimate that congestion costs the Dutch economy between €10 and €35 billion annually in lost business opportunities (Thijs Venema et al., 2024).

On top of this, effective electricity costs for large industrial consumers in the Netherlands are approximately 15% to 65% higher compared to peers in Belgium, Germany and France (Ministry of Economic Affairs, 2024). With grid tariffs expected to rise by 53% by 2034 (TenneT, 2024b), the competitive disadvantage of Dutch industry is set to increase even further, making cost-effective flexibility solutions more urgent than ever.

In response to these pressures, the market is shifting to new mechanisms that reward demand-side flexibility aiming to bridge this national tariff gap. One example is the ATR85/15 contract model, which limits industrial grid users to 85% of their contracted capacity, while allowing grid operators to curtail supply during the remaining 15% of the time. To benefit from such contracts without curtailing production, companies must adopt flexible strategies, either by adjusting production or by integrating ESS. For energy-intensive sectors like chemicals, where continuous process requirements limit curtailment options, ESS offers a potential pathway to unlock flexibility. Studies indicate that by combining ESS with time-based tariffs and flexibility contracts, Dutch chemical sites can reduce electricity costs by up to 65% (van Druten, 2024). Emerging pricing structures that promote flexibility strengthen the business case for ESS (TenneT, 2024d). For the highly energy-intensive Dutch chemical industry (see section:1.1), reducing electricity costs is essential to remain internationally competitive.

Moreover, the implementation of flexible energy contracts and time-based tariffs not only strengthens the business case for SDES but also paves the way for broader integration of LDES such as Iron-air. While SDES accounted for approximately 93% of operational storage capacity globally in 2021, LDES is expected to play a transformative role in decarbonizing industry (Guerra, 2021). As discussed in section: 2.1, the variability of solar and wind power requires storage solutions capable of bridging multi-day gaps between supply and demand, a role short-duration systems cannot fulfil alone. Pairing LDES with renewable energy sources could reduce global industrial greenhouse gas emissions by up to 65%. In the Netherlands, where electricity price volatility and carbon taxation are rising, the economic case for LDES becomes increasingly compelling (LDES Council & Roland Berger LP, 2023).

As the energy market shifts toward time-based pricing and flexibility incentives, the need to explore and implement optimal ESS strategies becomes more urgent. This is particularly true for energy-intensive sectors like chemicals, where continuous and inflexible demand is fundamentally misaligned with intermittent REG. In such contexts, ESS are not just beneficial, it is essential to unlock the full potential of emerging market mechanisms such as the ATR85/15 discount contract.

3 Research approach

This chapter introduces the multi-method research approach adopted in this study to ensure analytical depth and practical relevance. The research investigates the complementary roles of SDES and LDES in enabling the electrification of existing chemical production processes. Central to this analysis is the impact of variable REG profiles on the optimal installed capacity of different ESS. The research is structured in three main phases:

1. The literature review (section 1.2 and chapter 2)
2. The quantitative modelling phase (section 4 and 5)
3. Qualitative industry expert interviews for results validation (section 6)

This chapter begins by explaining the case selection approach, followed by the modelling framework, and concludes with the rationale behind the qualitative validation. The overarching goal is to identify the cost-optimal ESS configuration for a local renewable energy system tailored to the Dutch chemical industry. The combined insights from all three phases contribute to an embedded assessment on the configuration parameters with practical industrial relevance.

3.1 Case study

One specific Dutch chemical plant is selected for the case study within this research. To derive the most useful conclusions for the chemical industry, strategic sampling is applied to select the most promising chemical plant. Key selection criteria are:

- High dependency on energy and sensitive to price increases
- Positioned in a grid-congested area
- Demonstrated willingness to transition to renewable energy and pursue energy autonomy

To make this specific, numbers from the Central Bureau of statistics are applied visualizing the geographical distribution of chemical plants and refineries within the Netherlands. The size of the blue circles in Figure 8 represents the proportion of chemical plants and refineries within each region (van Gessel-Dabekaussen, 2018). Larger circles indicate a higher concentration of chemical activity, while smaller circles reflect a lower share. Subsequently, a figure from Netbeheer Nederland indicating local grid capacity was added as an overlay to the map, as the reliability of electrical energy becomes a greater challenge for chemical plants located in highly congested areas. The electrification of existing fuel-based processes will increase the demand for electrical energy of the plant, which will be constrained by existing grid congestion. Additionally, the business case for energy storage is most attractive in regions which are highly congested (LDES Council & Roland Berger LP, 2023).

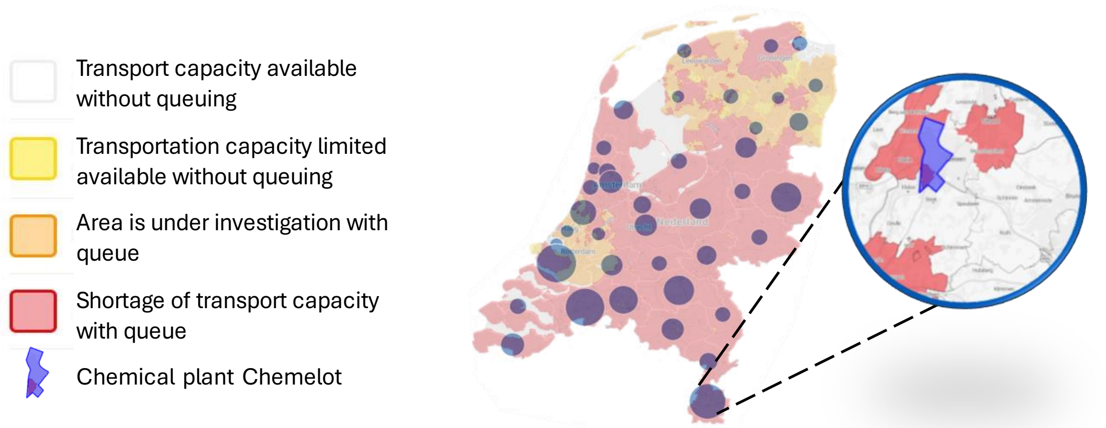

Figure 8: Geographical distribution of Dutch chemical plants combined with Grid capacity (Adapted from: Netbeheer Nederland, 2024; van Gessel-Dabekaussen, 2018)

Using this method, the Chemelot cluster was identified as a suitable case for this study. It is one of the largest Dutch chemical clusters, hosting more than 200 companies and 60 production facilities. Major multinationals such as SABIC (plastics), OCI Nitrogen (fertilizers/melamine), and Fibrant (caprolactam) play a leading role within the cluster (Chemelot, 2020). Chemelot is situated in the southern province of Limburg, which, according to grid overlays in Figure 8, is one of the regions experiencing significant grid congestion. This makes it a relevant case for exploring the opportunities of electrification and local energy solutions under physical grid limitations. Furthermore, Chemelot is aiming for the position to be Europe's leading 'circular chemistry site' with the goal of being fully climate neutral by 2050 (Chemelot, 2020). This confirms its willingness to transition to renewable energy or explore energy independence.

3.1.1 Electrified chemical process

The sixty plants within the Chemelot cluster are highly interconnected, forming one integrated system optimized for efficient use of energy, feedstocks, and residual streams, any adjustments in one part of the system affects the entire cluster (Chemelot, 2024). This means that electrification must occur incrementally, through carefully selected projects that secure system continuity.

To initiate this transition, Chemelot has identified several electrification projects, among which the deployment of a 20 MW electric steam boiler is a tangible first step. This project is part of their broad effort to decarbonize steam production. The e-boiler is designed to replace 30 tons of steam per hour using electricity instead of fossil fuels and is scheduled for commissioning in 2025 (Chemelot, 2024).

This e-boiler is able to replace part of the steam currently generated by high-pressure boilers, which are fuelled by natural gas and residual gases (Ouden et al., 2017). These conventional boilers are essential to balance site-wide steam demand, as total demand exceeds the volume of steam produced from exothermic chemical processes. The e-boiler could also serve as a flexibility pilot, contributing to demand-side response by offering controllable electricity usage, thus supporting grid stability.

However, the introduction of the e-boiler increases the site's electricity demand by 20 MW. Driven by multiple electrification initiatives, Chemelot its total electricity demand is expected to grow substantially, from 250 MW in 2020 to between 750 MW and 2,500 MW by 2050, representing a 200% to 900% increase depending on the chosen development pathway. The realization of these electrification projects depends not only on positive business cases but also on sufficient grid transmission capacity and the availability of renewable electricity. Currently, the site is limited to 375 MW of grid capacity, with a potential extension of 50 MW, a total of 425 MW remains insufficient even for the lowest expected future demand scenario (Chemelot, 2024). Therefore, this research investigates the potential of fulfilling additional electricity demand through local REG combined with ESS to secure electricity supply during periods of low wind and solar generation. The 20 MW electric boiler serves as the central case in the model and the remainder of this research. It represents a realistic example of additional electricity demand under grid constraints caused by the electrification of existing processes.

3.2 Quantitative modelling approach

The assessment of an optimal LES configuration to fulfil the additional electrified demand requires a structured analytical approach that integrates both technical and economic constraints. The model aims to support stakeholders involved in industrial energy strategy development. By simulating different deployment scenarios, it provides insight into how SDES and LDES can reduce total system costs associated with LES. Ultimately, it demonstrates how LES could enable electrification in grid-constrained regions and mitigate the risk of industrial economic migration from the Netherlands.

The remainder of this section continues by explaining the modelling question that guided the framework selection and gives an overview of its components and capabilities. Thereafter it outlines the data collection procedure followed by the different scenarios which are applied in the ESS assessment.

3.2.1 Modelling question

Following the principles outlined in the *Guide for Good Modelling Practice* (Nikolic et al., 2019), this section formulates the modelling question using the XLRM framework (Lempert et al., 2003). This structure helps to clearly define the system boundaries, the controllable policy levers, key uncertainties, and performance metrics to ensure transparency and relevance throughout the modelling process.

Figure 9 illustrates the XLRM framework regarding this study. The external factors (X) include uncontrollable but influential elements such as the electrified energy demand of chemical sites, the variability of REG profiles (solar and wind), elevated electricity price levels, and the availability of grid capacity. These factors lie outside the modeller's control, but they have a significant impact on system behaviour and outcomes.

The decision levers (L) are the decision variables that can be actively controlled by stakeholders. In this study, these include the availability and sizing of SDES and LDES, as well as the deployment of local REG from solar and wind. These levers represent strategic choices in designing LES under varying grid conditions.

The relationships in the system (R) capture the internal logic of the model, as implemented in PyPSA. These include the optimization of local REG, energy storage dispatch, and electricity demand balancing within a locally constrained grid environment.

The performance metrics (M) measure the outcomes of interest: namely, the optimal configuration of the components inside the LES and the associated total system costs. Total system costs include both CapEx and OpEx of the optimized LES configuration. These indicators reflect the techno-economic trade-offs between investment for reinforcing the external grid and investing in LES.

The modelling question based on the XLRM framework can therefore be formulated as:

"What is the impact of the availability and sizing of SDES and LDES technologies, and the deployment of local renewable generation (L), on the total system costs and resulting LES configuration (M), given the interactions between local renewable supply, storage dispatch, and electricity demand (R), under varying conditions of electricity demand, RES variability, price levels, and grid capacity availability (X)?"

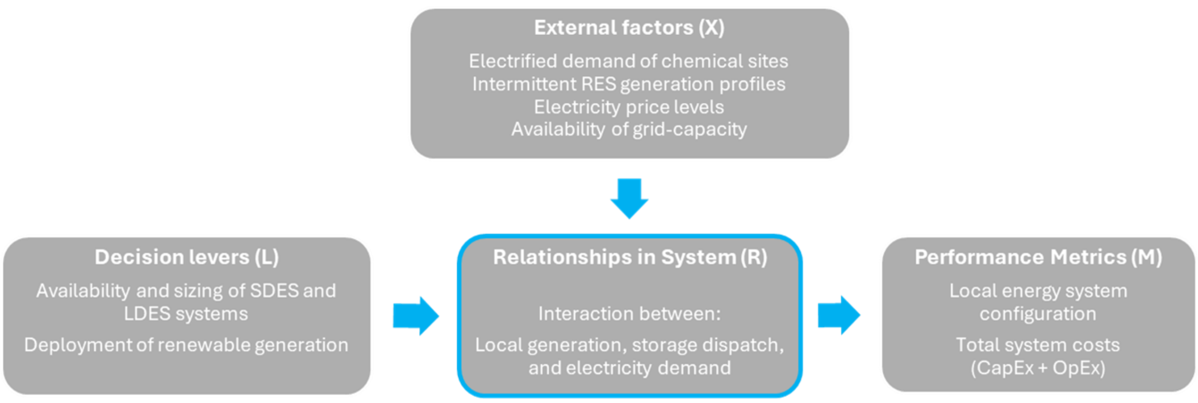

Figure 9: Modelling question structured using the XLRM framework (adapted from (Lempert et al., 2003))

3.2.2 Model framework comparison

Several studies within the reviewed literature used optimization models to assess the optimal configuration of energy systems on diverse levels. Within this research the different frameworks are compared on the following criteria:

Table 3: Model framework selection criteria including brief description.

Criteria	Description
Chemical process modelling depth	Level of detail in simulating chemical/industrial units (e.g. reactors, electrolysers), and energy system components.
Open source	Ability to inspect, modify, and extend the model for custom research. Ensuring transparency, accessibility, and reproducibility.
Temporal resolution	The size of time steps used in simulations, determining how accurately short-term dynamics or long-term energy strategies can be represented.
Spatial resolution	Level of geographic detail in the model: site-level, regional, or national
Software availability	The extent to which the model and its solvers are freely available (open access) or require commercial licenses, influencing ease of use, reproducibility, and research scalability.
Adaptability	Flexibility to support a wide range of scenarios, time resolutions, and system configurations, offering flexibility to address diverse research questions

Based on the reviewed literature, five modelling frameworks were selected for further assessment. These frameworks were identified through literature review of comparable studies in which similar energy system challenges were addressed, as listed in Table 4. The models applied in those studies served as inspiration for this research. Ultimately, the selected frameworks are evaluated against the criteria defined earlier in Table 3 to determine the optimal framework for modelling LES for the Dutch chemical industry.

Table 4: Modelling approach and framework of comparable studies

Author and year	Objective	Model Framework	Type of system
(Prenzel et al., 2025)	Decarbonization concept of a chemical site utility system	TOPENERGY	Renewable Power Purchase Agreement (PPA) + green H_2 + TES
(Bleys, 2025)	Optimal placement of large-scale BESS	PyPSA + Gurobi solver	SDES BESS + Grid expansion
(Du et al., 2025)	Assessment of ESS requirements for RES chemical plants with no grid connection and no REG curtailment	Aspen Plus + Chemkin	Green ammonia production with Lithium and H_2
(Wang et al., 2020)	Sector coupling with wind power and battery storage	gPROMS Dynamic optimization	Ammonia-Nitric acid with Wind and BESS
(C. Chen & Yang, 2021)	Process flexibility with optimized energy storage to minimize the levelized cost	GAMS + CPLEX solver	Methanol production plant

Table 5 below summarizes the comparative evaluation of all frameworks based on the criteria defined in Table 3, and PyPSA emerges as the most suitable modelling framework for this research. It is fully open-source and well-documented, supported by an active community and a continuously maintained GitHub repository (Brown et al., 2018). Compared to other frameworks like Aspen Plus or gPROMS®

that focus on in-depth chemical process-level simulations, PyPSA enables insights on a higher energy system-level by optimizing investment and dispatch of generation, storage, and grid infrastructure. Prior studies have validated PyPSA's capability to handle integration of renewable energy and battery storage in decarbonization scenarios (Bleys, 2025). Its adaptability, transparency, and proven use in academic and planning contexts make it highly effective for evaluating techno-economic trade-offs in LES design.

Table 5: Model framework comparison (++ = Excellent, + = Good, +- = Moderate, - = Limited, -- = Very limited or not supported)

Criteria	TOPENERGY	PYPSA	Aspen Plus	gPROMS	GAMS
Process modelling depth	+ -	-	+ +	+ +	+
Open source	-	+ +	-	-	+
Temporal resolution	+	+ +	-	+ +	+ +
Spatial resolution	+	+ +	-	-	+
Software availability	-	+ +	-	-	+
Adaptability	+	+ +	-	+	+ +

The following sections provide a detailed explanation of the PyPSA framework and its application in this study, including the modelled components, system design, and optimization objective.

3.2.3 PyPSA conceptualization

Python for Power System Analysis (PyPSA) is an open-source modelling framework for simulating and optimizing energy systems. It is designed for techno-economic analysis of energy generation, storage, and network infrastructure over multiple time steps, and supports the co-optimization of both investment and dispatch decisions (Brown et al., 2018).

Within this research, the PyPSA framework is adapted to represent the energy system of a Dutch electrified chemical plant or process. The model includes fixed demand profiles (loads), local REG technologies (solar and wind turbines), and storage units (SDES and LDES).

This research specifically aims to evaluate the role and synergy of SDES and LDES within a LES under constrained grid access. For different configurations of SDES and LDES sizing and generation deployment (L), and given external factors such as electricity demand and grid availability (X), the model identifies the cost-optimal configuration that minimises total system costs while meeting the additional electricity demand resulting from electrification (M).

The model co-optimizes LES investments of REG and ESS, which allows for the comparison with grid import/export under techno-economic and physical constraints. A Dutch chemical site is modelled as a node within a simplified electricity network, subject to hourly energy balance constraints and a limited grid connection. Figure 10 provides an overview of the energy system model used in this research in which the shaded blue region represents the LES as the main focus of the research.

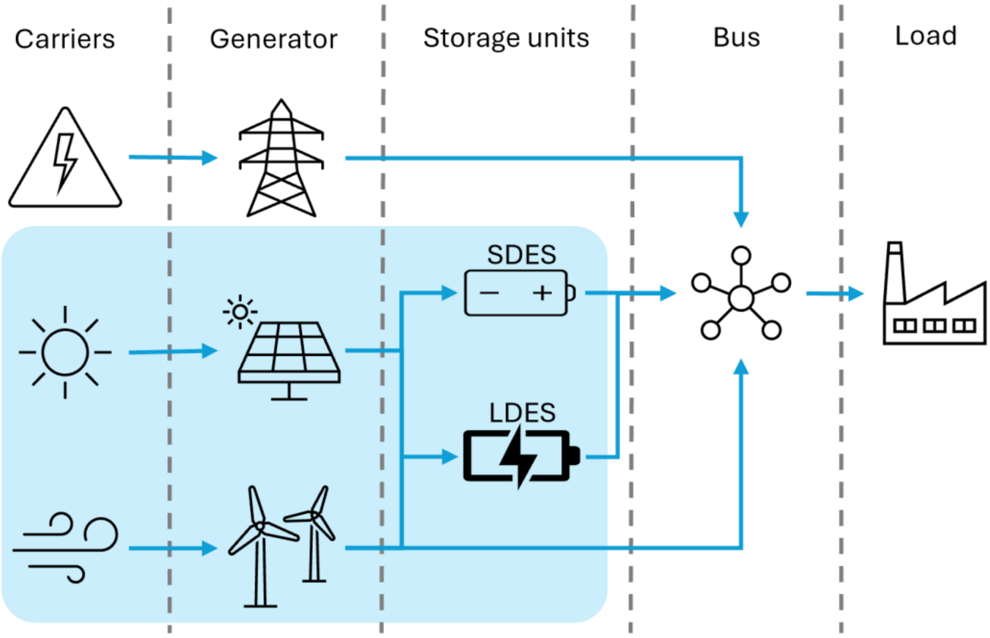

Figure 10: Conceptual system diagram of local energy model in PyPSA.

The system consists of one node with several core components: RES such as solar and wind generation, a simplified electricity grid, energy storage units (representing both SDES and LDES technologies), and fixed industrial load representing electrified chemical demand. Excess REG that cannot be used or stored is accounted for as curtailment, while any remaining demand is supplied via grid import. The vertical columns represent the component categories, while the blue arrows illustrate the electricity flow interactions between them as modelled in PyPSA. The model captures the dispatch of REG, the charging and discharging of storage units, and the balancing of supply and demand within the system's technical and capacity constraints. Table 6 gives a description of the key PyPSA model components used in the research, explaining their roles, properties, and how they aim to represent the LES to meet the electrified energy demand.

Table 6: PyPSA system components description

Buses	Buses function as central connection points for all system components (loads, generators, storage). For this research, a single electricity bus represents the LES, where all electricity flows are balanced.
Carriers	Carriers represent energy types like electricity, wind, solar, lithium, or Iron-air. While not physical components, they are important for grouping and assigning costs, uniformity in output, and constraints to model elements.
Snapshots	Snapshots define the temporal resolution of the model. Within this study they span one year at hourly intervals (8760-time steps), which allows for capturing seasonal and daily variability in REG and demand.
Loads	Loads define the given electricity demand profiles of the chemical plant. These are not controllable and must be met at each time step, reflecting the continuous energy needs of industrial processes.
Generators	Generators represent the power plants (fuelled with coal or natural gas) and REG, specifically solar and wind turbines in this case. Their output is time-dependent, constrained by hourly capacity factors (p_max_pu), and their installed capacity is optimised during the simulation (p_nom_extendable=True).
Storage Units	Storage Units are used to model energy storage technologies such as lithium-LFP (SDES), and iron-air batteries (LDES). They are characterised by power and energy capacity, round-trip efficiency (RTE), maximum discharge duration (max_hours), and optional cyclic state of charge.
Costs and Constraints	All components include capital and marginal costs. Generators and storage units also include efficiency losses, capacity expansion constraints, and operational limits.

PyPSA enables scenario-based simulation, where storage units and generators deployment levels can be selectively activated or constrained. This flexibility is essential to assess the techno-economic impact of deploying SDES and LDES under varying renewable deployment- and grid capacity scenarios. In each scenario, the model solves a linear optimisation problem to determine the lowest system-costs configuration that satisfies all system constraints. The explanation of system constraints and the system-costs is given in section: 3.2.4 and 3.2.5.

While the PyPSA framework provides the core optimisation engine, this research contributes by system-level analyses on hybrid ESS configurations tailored to Dutch chemical electrification facing grid congestion. This includes the selection and parametrisation of input data for electricity demand, REG availability, grid limitations, and ESS-specific cost and performance assumptions. Special attention is given to the accurate representation of storage sizing, discharge duration, and round-trip efficiency, ensuring both short-duration and long-duration use cases are adequately represented.

The resulting model quantifies the initial trade-off between external grid reinforcement and investment in LES, offering actionable insights into the system-level role of ESS in grid-congested industrial environments.

3.2.4 System boundaries

To ensure the model is realistic while sufficiently focused for meaningful analysis, the following system boundaries are defined:

Geographical Scope | The model covers the area of a Dutch chemical site. The site is represented as a single import/export node with limited capacity (contracted power capacity [MW]). No explicit transmission network or spatial congestion within the national grid is modelled.

Temporal resolution | The simulation spans one full year at hourly resolution (8760-time steps) to capture seasonal and daily variability in demand and REG.

Technological boundary | The model includes a simplified LES consisting of variable RES (solar and wind), SDES modelled as lithium-LFP batteries, and LDES represented by iron-air batteries. Based on the literature gap explained in section 1.2.4, this research specifically focuses on ESS by distinguishing between SDES and LDES, to reflect the dual need for managing both intraday power fluctuations and long duration energy shortages caused by renewable intermittency. While lithium-LFP remains the dominant SDES technology due to its maturity and efficiency, this study contributes to the literature by exploring the under-examined potential of hybrid storage systems that combine SDES and LDES in industrial settings like the Dutch chemical sector.

Energy carrier scope | The model exclusively optimises electrical energy flows and does not consider sector coupling, such as heat integration or hydrogen conversion. As a result, the analysis provides a focused assessment of the role of ESS in balancing electricity supply and demand, independent of interactions with other energy carriers.

3.2.5 Modelling objective

The objective of PyPSA is to minimize total energy system costs while meeting the constraint of supply must meet demand at each moment in time (snapshot. The cost function consists of investment (CapEx) and operational cost components (OpEx) associated with REG technologies, ESS, and grid expansion. The constraints and annuity factor are described in Appendix C.

For the optimization model, investment costs (CapEx) are represented by costs related to installing the optimal capacity [MW] of generation ($\bar{g}_{n,s}$) and storage ($\bar{h}_{n,s}$) technologies, as well as expansion in grid infrastructure (F_l), each multiplied by their respective annualised capital costs ($c_{n,s}$, c_l) [€/MW]. The operational costs (OpEx) are calculated over all time steps (t), based on dispatch levels ($g_{n,s}$) and ($h_{n,s,t}$) weighted by the time step factor (w_t) and marginal cost ($o_{n,s,t}$) [€/MWh] (Brown et al., 2018). Formally, the total system cost is minimised as shown in Equation 2, where the blue terms represent the capital expenditures (CapEx), and the green terms represent the operational expenditures (OpEx):

$$\min\left(\sum_{n,s} c_{n,s}\bar{g}_{n,s} + \sum_{n,s} c_{n,s}\bar{h}_{n,s} + \sum_{l} c_l F_l + \sum_{t} w_t\left[\sum_{n,s} o_{n,s,t}\, g_{n,s} + \sum_{n,s} o_{n,s,t}\, h_{n,s,t}\right]\right)$$

Equation 2: Optimization formalization

where:

- n : Node (location)
- s : Technology type
- l : Grid connection
- t : Time step (Hourly [h])
- c : Annualised capital costs of extending by one MW [€/MW]
- o : Marginal operational cost of dispatch for one MWh [€/MWh]
- w_t : weight of time t [h/year]
- g, h: dispatch of generator or storage [MW]
- $\bar{g}_{n,s}$, $\bar{h}_{n,s}$, F_l : optimised capacities for generation, storage, and grid connection [MW]

This formulation allows the model to co-optimise investment and dispatch decisions across all technologies, under technical and economic constraints, to identify the most cost-optimal energy system design for the electrified part of the chemical plant within a one-year simulation horizon.

3.2.6 Data collection

Open-source accessibility is one of the key selection criteria explained in section 3.2.2 for using PyPSA. Because open source-based frameworks ensure transparency, accessibility, and reproducibility. Therefore, this research primarily includes open-source data when available.

The data required to run the model can be categorized in (1) demand and supply, (2) Technology specific data, and (3) external grid related data. The data is gathered from a combination of empirical time series, technology cost datasets, and scenario-based assumptions. This includes hourly electricity demand profiles for a representative Dutch chemical site, time series for wind and solar generation potential, and techno-economic parameters for REG and ESS technologies.

Supply & Demand | The demand data is derived from process-level electrification assumptions from case-company publications (Chemelot, 2024). These are adjusted to reflect realistic industrial load shapes. Supply data on the other hand is generated from REG profiles (solar and wind) based on publicly available per-unit datasets from (Pfenninger & Staffell, 2016), these are corrected for local conditions and aligned with the model's hourly time resolution.

Technology input | Technology-specific input such as: investment costs, efficiencies, lifetime, and fixed/marginal operation and maintenance costs are sourced from the various papers, with findings normalised and compiled to serve as model input (FormEnergy, 2023; Schmidt & Staffell, 2023). The specific values are listed in the next section 3.2.7. These values are annuitized internally in the model to reflect annualised capital costs (according to Appendix C), allowing for proper comparison consistent with PyPSA's optimisation structure.

Grid expansion | The capital and operational costs related to grid expansion are derived from the official Dutch TSO (TenneT) 2025 tariff structure, based on the ACM-regulated investment and tariff calculation sheet (ACM, 2024). Capital expenditures (CapEx) are based on the projected investment values for high voltage (HS) grid connection infrastructure. Operational expenditures (OpEx) include fixed annual fees, contracted capacity tariffs [€/kW/year], and load-dependent charges. These grid expansion costs are not incorporated into the PyPSA optimization model itself but are instead calculated externally and used as a benchmark for the base case scenario. This approach allows for a cost comparison between conventional grid reinforcement and LES deployment.

Electricity prices | When the additional electrified energy demand of the chemical process is met via grid-expansion the electricity must be purchased on the wholesale energy market. The electricity prices used to complete the trade-off between grid-expansion and LES deployment in this study are based on raw wholesale day-ahead market prices as published by ENTSO-E. These prices exclude VAT, taxes, and levies, and reflect only the market clearing outcome of supply and demand matching (Entso-E, 2025). The year 2025 was selected as it represents the most recent complete dataset available.

3.2.7 Model input parameters

The technology-specific input parameters are selected with care based on the reviewed literature. The technological input parameters are divided into:

1. **Generators**
   - Solar PV
   - Onshore Wind
2. **Storage units**
   - Lithium-LFP (SDES)
   - Iron-air (LDES)

They correlate with the different components as generally described in section 3.2.3. This section starts with the relevant input parameters for the generators as summarized in Table 7 they include:

1. **Investment cost** [€/kW], representing the capital expenditure required to install a unit of REG power capacity.
2. **Lifetime** [years], indicating the expected technical lifespan of the technology.
3. **Fixed Operation and Maintenance** (FOM) costs, expressed as a percentage of the investment cost per year, which cover annual expenses like land lease, or insurance, regardless of output.
4. **Variable Operation and Maintenance** (VOM) costs are defined per unit of electricity generated, reflecting costs like component wear, cleaning, or repairs during operation.

Since this study does not aim to compare solar and onshore wind in detail, the input values for these technologies are directly adopted from the open-source PyPSA framework (Brown et al., 2018). This ensures consistency with the model environment while allowing the analysis to focus on the core research objective: the role of different storage duration technologies in cost-optimal LES design.

Table 7: Input parameters for REG technologies

Technology	Parameter	Value	Unit	Source
Onshore wind	FOM	1,2167	%/year	(Brown et al., 2018)
Onshore wind	VOM	1,4286	€/MWh	(Brown et al., 2018)
Onshore wind	Investment	1.095,8533	€/kW	(Brown et al., 2018)
Onshore wind	Lifetime	30	Years	(Brown et al., 2018)
Solar PV	FOM	2	%/year	(Brown et al., 2018)
Solar PV	VOM	0,0106	€/MWh	(Brown et al., 2018)
Solar PV	Investment	543	€/kW	(Brown et al., 2018)
Solar PV	Lifetime	40	Years	(Brown et al., 2018)

Secondly, the input parameters for ESS are presented in Table 8 and include the following economic and technical characteristics that define the performance and cost structure of storage technologies:

1. **Power-specific investment cost** [€/kW], representing the capital cost of installing the inverter which is the charging/discharging unit that defines the maximum power of the system.
2. **Energy-specific investment cost** [€/kWh], referring to the capital cost of the energy storage medium (e.g., lithium-LFP cells or iron-air modules), which defines the total storage capacity.
3. **Lifetime** [years], indicating the expected technical lifespan of the storage system, based on round-trip cycles or calendar degradation.
4. **Round-trip efficiency (RTE)** [%], reflecting the fraction of input electricity that is returned to the system after a full charge-discharge cycle.

The values are derived from recent literature sources and reflect typical assumptions for lithium-LFP as a representative of SDES, and iron-air as a representative of LDES. All values have been selected based on literature and harmonized with the modelling approach to enable transparent comparison across technologies.

Table 8: Input parameters for storage technologies

Technology	Parameter	Value	Unit	Source
Lithium-ion LFP	FOM	0,77	%/year	(PNNL, 2024)
Lithium-ion LFP	Round Trip Efficiency	92	%	(Viswanathan et al., 2022)
Lithium-ion LFP	Investment	64,62	EUR/kW	(PNNL, 2024)
Lithium-ion LFP	Lifetime	16,00	Years	(PNNL, 2024)
Lithium-ion LFP	Investment	182,00	€/kWh	(PNNL, 2024)
Lithium-ion LFP	Lifetime	16,00	Years	(PNNL, 2024)
Iron-air	FOM	1	%/year	(FormEnergy, 2023)
Iron-air	Investment	20	€/kWh	(FormEnergy, 2023)
Iron-air	Lifetime	30	Years	(FormEnergy, 2023)
Iron-air	Round Trip Efficiency	45	%	(FormEnergy, 2023)

The values above illustrate the fundamental trade-off in design characteristics. SDES technologies are associated with high round-trip efficiency and relatively low power-specific investment costs, making them suitable for short-duration, high-power applications. LDES technologies, such as iron-air, are designed to store large amounts of energy over extended durations at low capacity-specific cost [€/kWh] but typically involve higher power-specific investment costs and lower efficiencies.

In the technological assumptions, no separate inverter cost is included for the iron-Air technology. This is due to a lack of publicly available data and the expectation that inverter-related costs are relatively minor compared to the storage medium investment, especially for this long-duration, low-power system. For iron-air most of the investment cost lies in the storage medium, since the iron-air storage medium is primarily characterized by low energy cost [€/kWh] and high power-specific investment cost [€/kW] as explained in section 2.4. Moreover, the high energy-to-power ratio of iron-air systems (i.e. long discharge durations) means that the power component contributes less to total system cost. As a result, no separate inverter cost is modelled for iron-air in this study, as its exclusion is not expected to affect outcomes or conclusions substantially.

3.2.8 Scenario design

Within this research the model is developed to assess four objectives:

1. Quantify the impact of grid congestion on the feasibility of electrification in the Dutch Chemical industry
2. Evaluate the economic trade-offs between grid expansion and LES
3. Compare the impact of different ESS technologies on total energy-system costs
4. Compare the impact of different REG configurations, fluctuating demand profiles and reduced SDES CapEx, on the ESS selection and sizing

To assess the first three objectives, three scenarios will be evaluated and compared to a base case. The fourth objective will be addressed through a sensitivity analysis, as explained later in section 3.3.1. The PyPSA model allows to selectively activate and constrain deployment levels of all individual components such as storage units and generators. The following scenarios are assessed in this research and described in the remainder of this section.

- On-Grid | BASE CASE, Grid capacity expansion

A. Off-Grid | Local energy system (REG + SDES only)

B. Off-Grid | Local energy system (REG + LDES only)

C. Off-Grid | Local energy system (REG + SDES & LDES)

Base Case Grid expansion | The first scenario serves as the base case, representing a conventional real-world approach in which a chemical plant fulfils the increased electricity demand by requesting additional grid capacity at the TSO or DSO. This demand is met through grid expansion, with the associated investment and operational costs assessed using the methodology described in section 3.2.6. All subsequent scenarios are evaluated in comparison to this base case, allowing an initial trade-off between continued reliance on grid infrastructure and decentralized LES.

A Local energy system SDES | This second scenario represents a case in which no additional grid capacity is available to fulfil the additional electrified demand. To continue electrification a LES will be deployed with renewable generators (solar and wind) combined with Lithium-LFP as SDES system.

B Local energy system LDES | The third scenario runs a simulation comparable to A. However, instead of including exclusively SDES this scenario only includes LDES to bridge power shortages in REG. Both solar and wind generation are still optimized in this scenario, representing the scenario in which a chemical site is located in a grid-congested zone and willing to invest in a LES with REG and LDES.

C Local energy system SDES + LDES | This final scenario addresses the literature gap by evaluating a hybrid LES that combines both SDES and LDES technologies. The system is designed to meet the additional electricity demand using local resources only, with co-optimised deployment of renewables and both storage types. This configuration allows evaluation of the potential cost advantage of hybrid ESS compared to single-technology setups.

This model is designed to inform industry about alternative pathways for power capacity expansion because grid congestion and elevated electricity prices are acting as barriers for electrification in the Dutch chemical industry. This multi-scenario approach allows evaluation of the potential cost advantages of hybrid SDES–LDES configurations (Scenario C) over single-technology systems (Scenarios A and B) and compares them to conventional grid expansion (Base Case).

While Scenario C explicitly addresses the literature gap by evaluating the techno-economic performance of a hybrid ESS tailored to the needs of the chemical industry, Scenarios A and B serve as necessary reference cases. They isolate the contributions of SDES and LDES individually, enabling a systematic assessment of the added value of combining both technologies in Scenario C. Together, these scenarios enable robust comparison across centralized and decentralized system designs and support the evaluation of objectives 1, 2, and 3. The fourth objective will be tackled during the sensitivity analysis explained in chapter 5.

3.2.9 Modelling assumptions

To make the model useful within the limited time of this research, several assumptions are made:

1. Storage technology efficiencies are assumed constant over time; battery degradation and lifetime-dependent performance losses are not considered.
2. Weather and REG profiles are based on a single reference year (2024) and are assumed to be representative for the entire simulation period.
3. The model is electricity-only: sector coupling with or other energy carriers is not included.
4. The model operates under perfect foresight, meaning no uncertainty is considered in future renewable energy availability or demand.
5. Startup and shutdown costs and constraints are not modelled.
6. Spatial impacts and land constraints related to the deployment of REG and ESS are excluded.
7. Lithium-LFP and iron-air batteries are used as representative technologies for SDES and LDES, respectively; other technologies in these categories are not modelled.
8. Policy, regulatory, or permitting are excluded, which may affect practical LES implementation.

3.3 Research validation

In line with the principles of good modelling practice, this study applies a structured model evaluation approach. It combines input sensitivity testing to explore uncertainty with a qualitative validation method involving industry expert stakeholders (Nikolic et al., 2019).

3.3.1 Model validation

To assess the robustness of model outcomes under varying input assumptions, a sensitivity analysis is performed. This method increases confidence in the reliability of the results while generating a deeper understanding of the most influential factors. The sensitivity analysis is designed to evaluate the impact of changes in key input parameters (X and L) as defined in the XLRM framework (section 3.2.1) on the resulting performance metrics (M). This approach provides insights into how sensitive the optimal system configuration is to variations in assumptions such as the installed ratio between solar and wind capacity. The goal is to determine whether slight changes in the system's inputs lead to proportionally small or large shifts in outcomes like total system cost or storage capacity, thereby assessing the model's robustness.

3.3.2 Results validation

Beyond internal consistency, the model is also evaluated for external validity and practical relevance. A semi-structured interview is conducted with two industry experts which are working at a knowledge and innovation centre, they are accelerating the transition of the chemical industry toward climate neutrality, circularity, and enhanced safety. They operate at the interface between industry, academia, and government, translating scientific research into industrial applications. Both participants have an in-depth understanding of the technical and regulatory challenges facing industrial decarbonization. Their perspective makes them highly relevant for expert interviews, as they provide insights that bridge the gap between technological feasibility, market conditions, and policy frameworks to assess the usefulness and feasibility of the modelled LES configurations.

The interview focuses on the electrification potential of chemical processes and the feasibility of deploying REG and ESS close to chemical production sites. The goal is to strengthen the interpretation of the modelling results, which helps to determine whether the proposed solutions are not only cost-optimal but also viable under real-world conditions. It increases the external credibility of the research and ensures alignment with current industrial challenges and constraints. The interview protocol is given in Appendix D

4 Modelling results

Given the extensive amount of output generated, only the results most relevant to the research questions are included. As outlined in section 3.2.8, three LES scenarios are analysed, each varying in ESS availability. All scenarios are ultimately compared to the reference base case, where additional demand from the 20 MW e-boiler is met through grid expansion (section 4.1). By comparing different electrification pathways to supply the 20 MW e-boiler, this research provides a first step toward assessing the viability of different ESS within LES in the Dutch chemical sector.

For the modelled scenarios, the installed power of REG and ESS are presented. To illustrate the operational behaviour of each scenario, dispatch plots are provided over a 20-day period with variable weather conditions. This timeframe was deliberately chosen to capture a representative mix of high-wind, low-wind, and solar-dominant days, thereby highlighting how different REG patterns influence system operation. These visualisations show how supply, demand, curtailment, and storage interact over time, typically on an hourly basis. Each dispatch plot consists of the following key elements:

- **Power generation** is shown as stacked areas above the x-axis, with yellow representing solar and blue representing wind as generation technologies. The combined area reflects the total REG available at each moment in time.
- **Curtailment** is shown using hatched overlays on top of generation areas. This represents the difference between the maximum available REG (e.g., from wind or solar) and the power actually used. High curtailment indicates times when renewable output exceeds system flexibility or demand.
- **Demand** is illustrated as a dashed black line, which is mostly horizontal due to the continuous power demand of the e-boiler to supply the chemical plants on site.
- **Storage behaviour** is shown through positive and negative bars below and above the x-axis:
  - **Charging** appears as negative bars (green for SDES, and red for LDES), indicating that energy is being absorbed from the generators into the ESS.
  - **Discharging** appears as positive bars, showing energy supplied from storage to meet demand (also green for SDES, and red for LDES).
- **State of Charge (SoC)** of the ESS is plotted as a dashed line overlaid on the graph, linked to a secondary y-axis on the right. It indicates the relative amount of energy [kWh] within the storage unit over time (in %), revealing whether the system is storing excess energy or depleting reserves.

In addition to dispatch plots, the curtailment ratio (CR) quantifies the share of technically available REG that remains unused due to system constraints. Curtailment can be caused by limited demand, or misaligned storage power/capacity. CR is defined as the ratio of unused – to available REG over the period, where availability is derived from weather profiles $p_{max,pu}(t)$. The CR is given in Equation 3.

$$Curtailment\ ratio\ [\%] = \frac{E_{available,g} - E_{generated,g}}{E_{available,g}} \times 100$$

Equation 3: Curtailment ratio

Where $E_{available,g} = \sum_t p_{max,pu,g}(t) * p_{nom,g}\ \Delta t$ is the total technically available energy for generator g, and $E_{generated,g} = \sum_t p_g(t)\, \Delta t$ is the actual energy produced. A higher CR indicates that a larger share of available REG is not utilized, signalling misaligned storage power/capacity or oversized REG assets. Whereas a lower CR evidences effective ESS integration and temporal shifting of REG. A system-wide CR is obtained by summing $E_{available,g}$ and $E_{generated,g}$ over all generators before taking the ratio. In this study, the CR evaluates the extent to which ESS configurations reduce renewable spillage and enables scenario comparisons while controlling for weather-driven resource variability.

This chapter first presents the results of the base case (section 4.1), followed by the evaluation of each LES scenario (sections: 4.2, 4.3 & 4.4). section 4.5 concludes with the comparative assessment.

4.1 Base case | Grid Expansion cost Estimation

This base case scenario estimates the annual system costs for a Dutch chemical company that meets its additional electricity demand by expanding its grid connection. These costs include (1) the tariff for contracted transmission capacity with the grid operator and (2) the electricity costs based on actual consumption. The tariff structure for the additional power transport capacity is retrieved from the Dutch Authority for Consumers and Markets (ACM, 2024) while electricity costs are derived from ENTSO-E day-ahead market prices (Entso-E, 2025).

Each year, ACM sets the maximum tariffs that TenneT, the national transmission system operator, is allowed to charge for providing grid access and system services on the high-voltage (110/150 kV) and extra-high-voltage (220/380 kV) networks. This research uses the published ACM tariff structure to calculate the cost of a 20 MW industrial grid capacity expansion, based on the following components:

Table 9: Cost structure of grid expansion

Cost component	Value	Explanation
Fixed connection fee	€2,760 /year	Standard annual fee per connection regardless of power or consumption.
Contracted capacity fee	€73.46 /kW/year	Yearly fee based on the agreed maximum capacity.
Peak weighted capacity fee	€8.50 /kW/month	Fee based on the peak power consumed during the 5 highest-use hours of each day, averaged over the month
Total network costs	**€3,511,960 /year**	Sum of components above applied to the case
Average electricity price	€0.0773 /kWh	Based on Day-ahead prices of 2024 (Entso-E, 2025)
Electricity consumption	175,680 MWh/ year	20MW constant demand * 8784 hours (2024)
Total electricity costs	**€13,577,899 /year**	175,200 MWh × €0.0773/kWh
Total system costs	**€17,089,859 /year**	Network costs + electricity costs

This cost breakdown shows that expanding the grid connection to meet a constant 20 MW demand results in total annual system costs of €17.09 million. As shown in Figure 11, the electricity consumption relates to 79% of the total costs with €13.58 million, while grid infrastructure costs at €3.51 million account for the remainder. The sum of these values forms the base case for evaluating the cost-effectiveness of LES alternatives in subsequent scenarios.

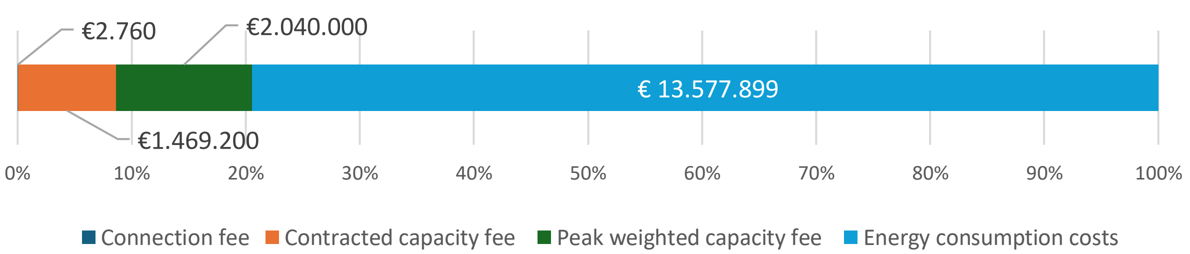

Figure 11: Total system costs grid expansion Base case.

This cost-based benchmark enables an objective assessment of the economic viability of LES by comparing avoided grid expansion costs with the investment and operational costs of decentralised REG and ESS.

4.2 Scenario A | LES + SDES

In Scenario A, the additional electricity demand regarding the installation of the 20MW e-boiler is supplied locally, without any grid connection. This system relies entirely on REG from solar and wind combined with lithium-LFP batteries (SDES) as only deployable ESS. The optimized capacities include:

- Wind: 144.4MW
- Solar : 21.0MW
- Lithium 6hr: 88.2MW

Total annual system costs amount to €26.6 million, making Scenario A the most capital-intensive LES configuration evaluated within this study. The dispatch plot in Figure 12 shows the interaction between REG and curtailment, storage charging and discharging, and the state of charge (SoC) of the battery as a percentage to its maximum energy capacity (MWh):

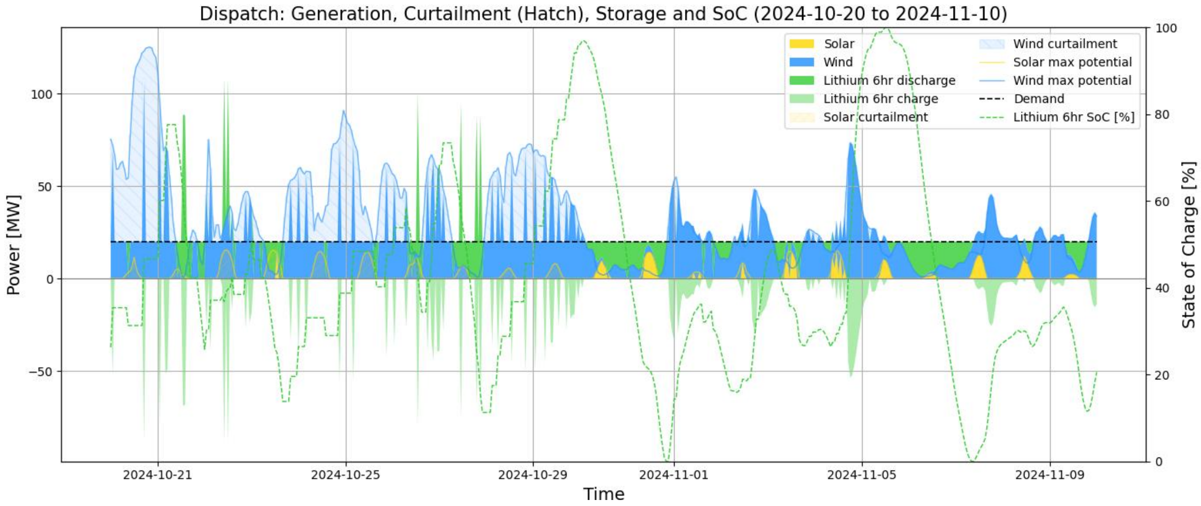

Figure 12: Power dispatch Scenario A October

Figure 12 plots the power dispatch of the installed technologies for scenario A in Autumn. Wind generation dominates the REG mix, with solar playing a supporting role, particularly for the short peaks when it is less windy, on the 30th of October for example. On this day SDES is discharging at max power (visualised by the steeply dropping green dashed line) and to prevent the need for even larger SDES energy capacity (kWh), solar is dispatched during wind lulls. An interpretation of the seasonal variation within this scenario A is described below based on the dispatch plots for each season. The dispatch plots are given in Appendix E.

- In autumn (October and early November), the system faces extended shortages in REG (e.g. 11-05 to 11-09), during which SoC frequently drops to zero, exposing its inefficiency to buffer multi-day gaps caused by the relatively high cost related to energy capacity [kWh] expansion.
- In winter (January), wind dominates generation which is largely curtailed representing the inability of SDES to store this energy. In contrast, SDES is used for high-frequency balancing, but lacks the energy capacity to cover multi-day lulls.
- In summer (June), solar output is available but largely curtailed. Li-6 is used to cover short REG dips, also when solar could contribute, the system mostly relies on oversized wind power.

These patterns confirm that SDES supports short-term balancing effectively but is insufficient for longer-duration energy shifting. As a result, REG power [kW] must be oversized to ensure energy supply is able to meet demand during periods of low wind and low solar radiation, driving up total LES costs and causing frequent curtailment. This is reflected in the high-curtailment ratio of 61.5% for wind and 89.93% for solar. Nonetheless the deployment of additional REG power remains more efficient compared to expanding energy capacity with the relatively expensive Lithium.

Overall, the 6-hour Lithium-LFP SDES undergoes frequent shallow cycles and occasionally deeper ones, but its limited duration and high energy capacity cost prevents it from mitigating structural mismatches between supply and demand. This highlights the system's dependence on oversized REG to maintain sufficient energy supply during REG shortfall in the absence of LDES.

4.3 Scenario B | LES + LDES

In Scenario B, the additional electricity demand from the 20 MW e-boiler is also supplied locally, without any external grid connection. However, this configuration relies solely on LDES represented by iron-air as ESS. It optimizes iron-air technology, combined with wind and solar. The model deploys the following optimized power capacities for REG and ESS to fulfil the 20MW of the e-boiler:

- Wind: 96.5MW
- Solar : 32.3MW
- Iron-air: 29.3MW

These capacities come with an annual total system cost of €16.83 million, therefore scenario B is substantially more cost-efficient compared to A (37% cheaper). This is largely attributed to the high energy-to-power ratio [kWh/kW] and low cost of iron-air energy storage capacity (kWh).

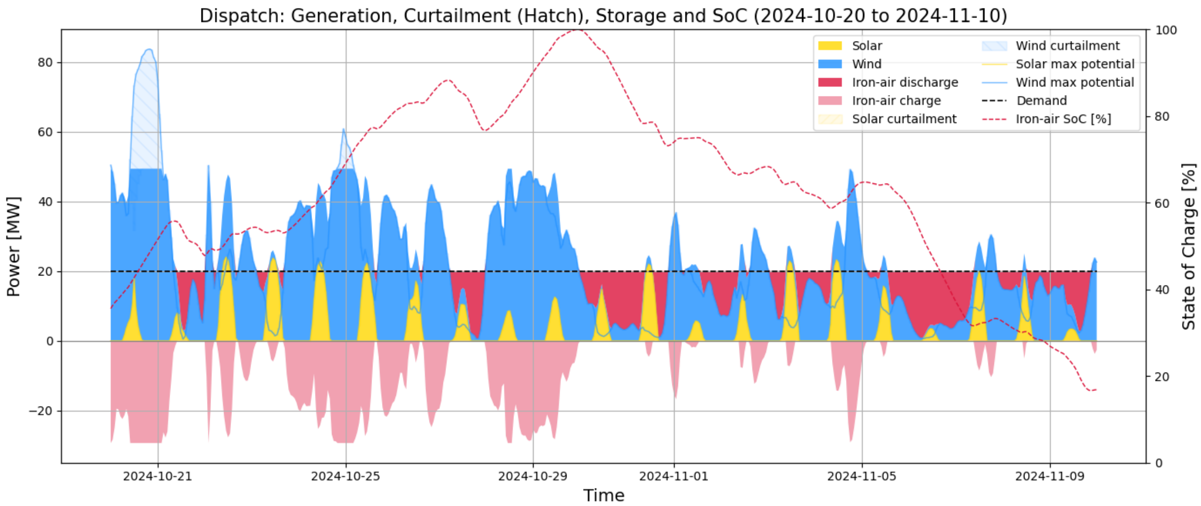

Figure 13: Power dispatch Scenario B October

Same as for scenario A in the previous chapter the dispatch plot for October (Figure 13) illustrates how the system operates under high and low REG conditions. The plots representing different seasons (winter, summer, and autumn) are given in Appendix E and resulted in the following insights:

- In autumn (October and early November), the battery shows the most dynamic behaviour, combining both shallow and deep cycles (SoC). This plotted period begins with a gradual build-up in SoC (red dashed line) followed by long-term discharge, reflecting the LDES ability to balance multi-day shortages in REG to meet demand within one charging cycle. In contrast to Scenario A | LES + SDES (Figure 12).
- During winter (January), wind dominates and is more intensely curtailed. The LDES SoC is less dynamic since wind is able to meet demand more easily reducing the need for ESS.
- In summer (June), solar and wind are more complementary. Solar generation leads to regular, daily cycles of the LDES, with clear patterns of charging at midday and discharging in the evening.

These seasonal dispatch dynamics confirm the flexibility of LDES to act across both daily and multi-day timescales, significantly improving the temporal alignment between variable REG and constant chemical demand. However, due to the relatively low power (kW) of LDES, deployment of solar remains cost-effective to secure supply during short wind drops with constant demand.

The resulting curtailment ratios of 48.32% for wind and 1.76% for solar indicate relatively efficient use of REG assets. These lower curtailment ratios can be explained by the ability of the LDES technology to better align the intermittency of RES (especially wind) with continuous demand, enabling more efficient utilization of REG capacity over time, reducing curtailment and the need for oversizing in REG.

4.4 Scenario C | LES + SDES & LDES

For the last Scenario C, the additional 20MW electrical demand is also fulfilled locally without external grid expansion. In this scenario, the model continues to use wind and solar for REG, but enables the combination of both SDES and LDES. With lithium-LFP with a duration of 1, 2, 4 and 6 hours and iron-air with a discharge of 100 hours as ESS technologies. The final optimised capacity configuration is:

- Wind: 96.5MW
- Solar : 32.3MW
- Lithium-LFP: 0.0MW
- Iron-air: 29.3MW

A notable outcome with 0.0MW is the absence of SDES (Lithium-LFP) deployment in the optimized configuration. Although the model had the option to combine lithium-LFP as SDES with LDES, it exclusively selected iron-air LDES instead. Therefore, the results show identical installed capacities in Scenario C compared to Scenario B, highlighting the model's preference for LDES under the given system constraints and cost assumptions.

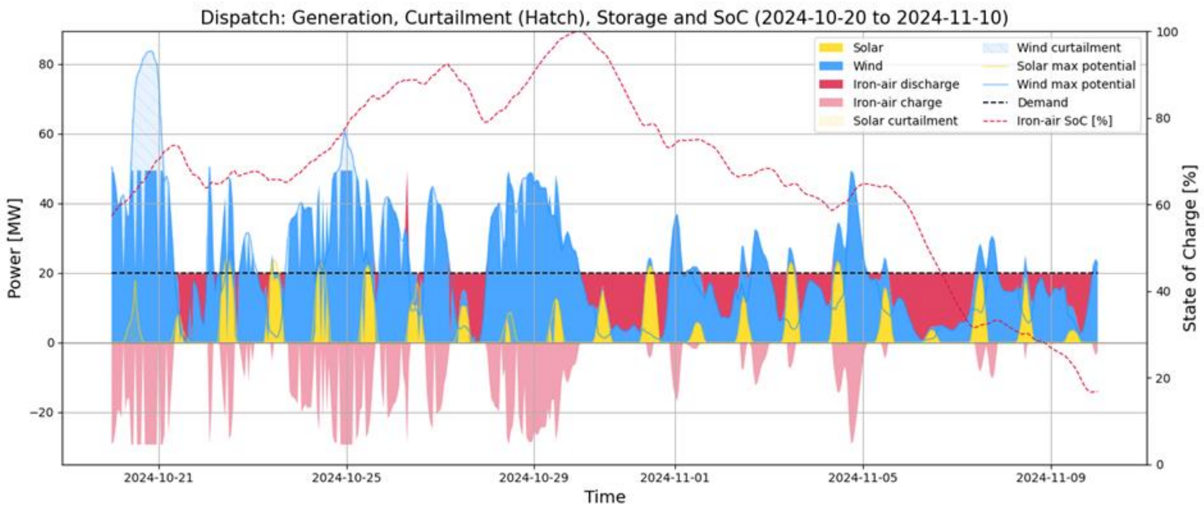

Figure 14: Power dispatch Scenario B October

Logically the power dispatch as shown in Figure 14 also remains comparable to the plot related to Scenario B (Figure 13). Similarly for the plots illustrating seasonal behaviour in Appendix E. Despite the exclusion of SDES, the system demonstrates sufficient flexibility and resilience, likely due to the large energy capacity (kWh) and low cost of LDES combined with its alignment between the selected REG assets and demand.

The resulting curtailment ratios in Scenario C are 36.83% for wind and 64.69% for solar. As evidenced by this high curtailment ratio, the system relies more heavily on wind generation compared to solar. It indicates that wind power is utilized more consistently throughout the year, while solar generation is curtailed more frequent. As shown in Figure 14 the iron-air charge (red area below x-axis) is effectively a mirrored version of the surplus wind generation (the blue area above the black dashed line of the demand at y=20). Meaning in this scenario LDES prioritizes capturing and discharging wind surpluses, which are often more temporally spread as explained in section 2.1, making wind a more dominant contributor to secure supply meets demand. Despite the identical capacity configuration in Scenario B and C the curtailment ratios differ. A deeper explanation for this difference is given in section 4.5.

4.5 Cost & capacity assessment

This section gives a direct comparison of technology deployment and cost impact between the base case and three LES configurations. A stacked bar-plot presents the installed power capacities (left y-axis) and annualized total system costs (right y-axis) across the four energy system scenarios (Figure 15). Each scenario suggests the optimised capacity deployment to supply the 20 MW of electrified demand from the e-boiler, with distinct technological constraints as defined in section 3.2.8. Each bar represents a scenario composed of different technologies. The technologies are color-coded, and the dashed black line represents the annualised total system cost for each scenario.

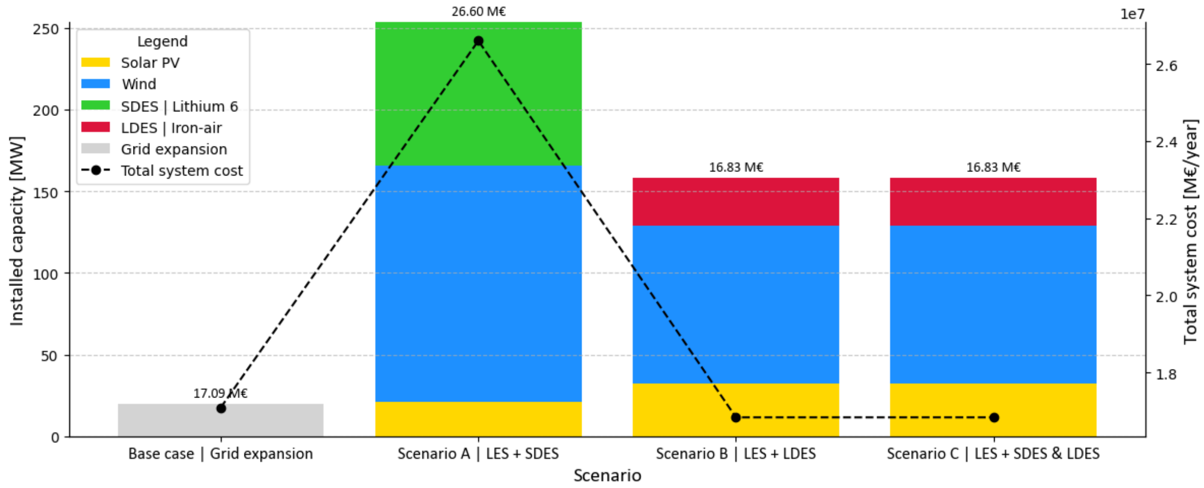

Figure 15: Optimized power deployment and total system costs across the base case and three storage scenarios.

Scenario A, which relies exclusively on SDES, results in the installation of 88.2 MW of lithium-LFP batteries with a discharge duration of 6 hours. In this configuration, the model prefers wind over solar generation, deploying 144.4 MW of wind versus 21.0 MW of solar. This heavy reliance on SDES combined with oversizing of wind leads to the highest total system cost (€26.6M), primarily due to the high capacity-specific investment cost of lithium technologies. In contrast, Scenario B allows only LDES. The model installs 29.3 MW of iron-air batteries, increases solar deployment with 54% to 32.3 MW, and reduces wind capacity with 33% to 96.5 MW. Wind plays a less dominant role in the generation since LDES enables large energy storage capacity [kWh] for long durations allowing for more utilization of wind energy (less curtailment). Within this scenario solar is typically deployed to supply high power output during short periods of low wind. Solar deployment is preferred over LDES expansion since the power capacity [kW] of LDES is relatively low. Scenario C allows for the optimization of a hybrid ESS configuration (both SDES and LDES), yet the model selects only LDES, resulting in an identical LES configuration compared to Scenario B. Together, B and C are the most cost effective at €16.8 million annually, indicating that iron-air is more cost-effective under the given conditions in the model.

These results suggest that LDES is the preferred storage technology for the chemical setting modelled, offering a more economical solution than LES with SDES. Hybrid configurations do not provide additional value under the given constraints unless cost structures or operational constraints change.

4.5.1 Dispatch comparison scenario

This section compares the dispatch patterns across the different scenarios by evaluating the curtailment ratio of each installed technology, as introduced at the beginning of this chapter. The curtailment ratio measures the share of technically available renewable electricity (REG) that remains unused. In this study, curtailment is driven primarily by temporal mismatches between generation and demand and by storage limitations (insufficient power/duration or SoC headroom). For the base case there is no curtailment ratio available since it represents a guaranteed electricity supply from the grid operator and no local REG is installed which can be curtailed. In this base case, the grid delivers a constant 20 MW to completely meet the e-boiler's demand at all times, resulting in full utilization of the installed grid connection. The curtailment ratios for the LES scenarios are given in Table 10.

Table 10: Curtailment ratio comparison

Technology	Base case Grid expansion	Scenario A LES + SDES	Scenario B LES + LDES	Scenario C LES + SDES & LDES
Solar	-	89.93%	1.76%	64.69%
Wind	-	61.50%	48.32%	36.83%
Aggregated curtailment	**N/A**	**62.96%**	**43.16%**	**39.92%**

Scenario A exhibits the highest curtailment ratio of all scenarios, especially for solar. This is primarily due to the SDES being unable to bridge multi-day mismatches between REG and the 20MW constant demand because it lacks sufficient storage capacity [kWh]. The model therefore prefers adding solar power rather than the costly SDES capacity [kWh]. As a result, solar peaks (particularly during summer) cannot be stored for later use and are often curtailed (~90%). Wind power is intentionally oversized to maintain supply during multi-day low-wind periods in winter, therefore wind also suffers from large curtailment (62%) during surplus events. The combination of intermittent REG, constant chemical demand, and storage that is misaligned in power/capacity leads to significant LES over-dimensioning and frequent curtailment, reducing utilisation and cost-effectiveness. System-wide, aggregated curtailment reaches 62.96%, meaning nearly two-thirds of the technically available renewable energy remains unused within LES scenario A.

Scenario B achieves remarkably lower curtailment ratios. With LDES, the aggregated curtailment drops to 43.16% (19.83 percentage points lower than A). This scenario shows the ability of LDES to shift summer PV and winter wind surpluses into deficit periods, reducing REG curtailment. The LDES improves alignment between REG and the constant demand, allowing excess REG to be stored and used later. This modelled LDES only scenario shows a notably low solar curtailment ratio (1.76%) and a wind curtailment ratio of 48.32% (lower than in Scenario A), indicating that PV output is predominantly used directly while wind surpluses are curtailed more frequently. This follows from the REG capacity mix: with only 21 MW of installed PV and 144 MW of wind, against a constant 20 MW process load, PV rarely exceeds demand even during high-irradiance hours, so little PV needs to be curtailed. As described in section 4.3 and illustrated in Figure 13, the LDES charging profile mirrors the wind surpluses. This confirms that when sunny hours coincide with windy conditions, the iron-air LDES preferentially charges with wind surpluses, leaving limited headroom to take additional PV peaks and thereby shifting curtailment towards wind. The ability to store both solar and wind for later usage reduces curtailment and enables better utilization of the installed REG capacity. The system operates more flexible across multiple timescales, resulting in lower curtailment ratios of both wind and solar.

Lastly, Scenario C yields lower wind curtailment (36.83%) but higher solar curtailment (64.69%), with aggregated curtailment of 39.92% (≈3.24 percentage points lower than B). The difference with scenario B needs further explanation because the LES configurations are identical. Both scenario B and C have identical installed REG and ESS capacities and equal total system costs, the variation in curtailment ratios highlight the difference in how the system dispatches renewable energy and the synergy with the ESS.

The total ESS throughput of the battery is used to explain this difference. ESS throughput measures the sum of charging and discharging at the ESS. In this study, it is applied to explain the different aggregated curtailment ratios in B and C: The ESS throughput of the LDES is 64.99 GWh in scenario B versus 95.25 GWh in scenario C (≈46.6% higher), meaning the LDES cycles more in scenario C. This is also visualized in Figure 16 with area below the SoC (dark-red dashed line) which is larger in scenario C compared to B. Combine this with the fact that the iron-air battery has a 45% round-trip efficiency, implicates sizable storage losses of ≈24.5 GWh in B versus ≈35.9 GWh in C. These storage conversion losses must be covered by additional REG production since demand remains identical (20 MW constant). That extra REG would otherwise be curtailed, so higher ESS throughput in C absorbs more REG surplus which reduces total curtailment. At the same time, more frequent ESS cycling can leave less SoC headroom during sunny peaks, shifting the composition of curtailment (e.g., relatively more PV curtailment and less wind curtailment) even as system-wide curtailment falls.

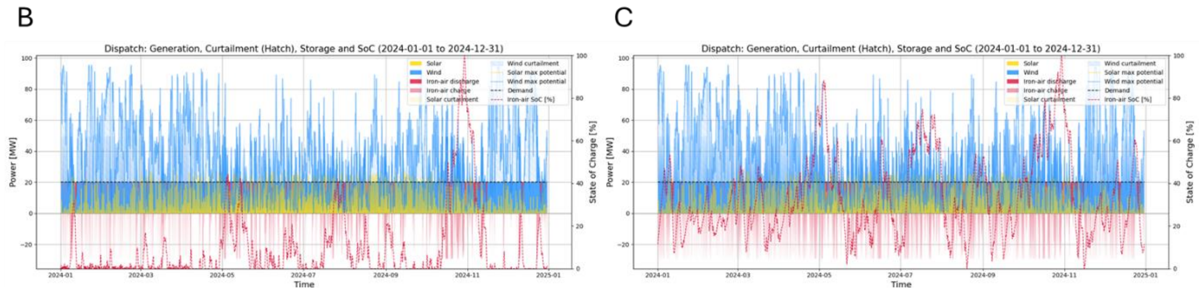

Figure 16: Full year-round dispatch plot scenario B and C

Scenario C is likely to utilize wind energy as dominant RES since the curtailment ratio of 36.83% is considerably lower compared to 64.69% for solar. This reflects a better utilization of wind energy. In contrast, Scenario B demonstrates a less balanced use of wind and solar with curtailment ratios further from each other. The relatively lower solar curtailment ratio in B compared to C indicates that solar energy is utilized more actively to directly meet demand or using it to charge the LDES.

These findings imply that different degrees of freedom in deployable ESS can affect how REG technologies are utilized, despite having identical optimized LES configuration and cost structure. The model does not distinguish between spilling PV or wind in surplus hours. This means that multiple dispatch profiles can be cost-optimal. Furthermore, the presence of SDES as an option in C pushes the solver to a different dispatch profile, changing when LDES charges/ discharges, and thus shifts the composition of curtailment (e.g., relatively lower wind curtailment and higher solar curtailment in C) even though total costs and installed capacities match.

Nonetheless, the absence of SDES in Scenario C simply means that the optimizer finds no cost-effective role for SDES under the given system configuration and demand profile.

4.5.2 Base case comparison

When comparing the LES scenarios to the base case with grid expansion, LES configurations emerge as slightly more cost-optimal alternatives within the modelling constraints, as long as LDES is included for modelling (Scenario B & C). The most optimal LES emerges in scenario C with a total annual system cost of €16.8 million compared to €17.1 million for the base case and the lowest aggregated curtailment ratio of 39.92%. While the comparison between the base case and a LES scenarios offers useful insight into cost structures and ESS strategies, the insights from the qualitative analysis with industry experts highlights that full comparison between grid expansion and LES requires the inclusion of additional components in the cost structure of an LES which fall beyond the scope of this research. Therefore, this analysis provides a first evaluation of energy system-level conclusions, further explanation of the missing components is given in section 6.2 and 7.1.3.

5 Sensitivity analysis

This section presents a sensitivity analysis aimed at evaluating the influence of key input parameters on model outcomes. Aligned with the XLRM framework (section 3.2.1), the analysis focuses on variations in exogenous factors (X) and decision levers (L), and examines their effect on performance metrics (M). The objective is to assess the robustness of the optimal system configuration by determining to what extent slight changes in input assumptions lead to proportional or disproportionate shifts in key outputs, such as total system cost or installed storage capacity. The sensitivity of the model is explored on three assumption:

1. The impact of the installed REG mix (solar vs. wind) on the ESS configuration.
2. The effect of a more fluctuating electricity demand profile on system configuration.
3. The influence of reduced investment costs for SDES.

5.1 Generation ratio

Firstly, the influence of different REG portfolios on the ESS configuration. A sensitivity analysis is conducted using two scenarios in which the availability of REG technologies is restricted. Starting by assuming a system with 100% solar, while the second considers 100% wind energy. These are compared against the hybrid LES configuration of scenario C, as described in section 4.4.

Figure 17 presents a stacked bar chart showing installed power capacities (left y-axis) and total system costs (right y-axis) for the three scenarios. Technologies include solar, wind, two variants of lithium-LFP batteries (2h, 4h), and iron-air storage (LDES). Total system cost is indicated by a dashed line with numeric labels above each bar.

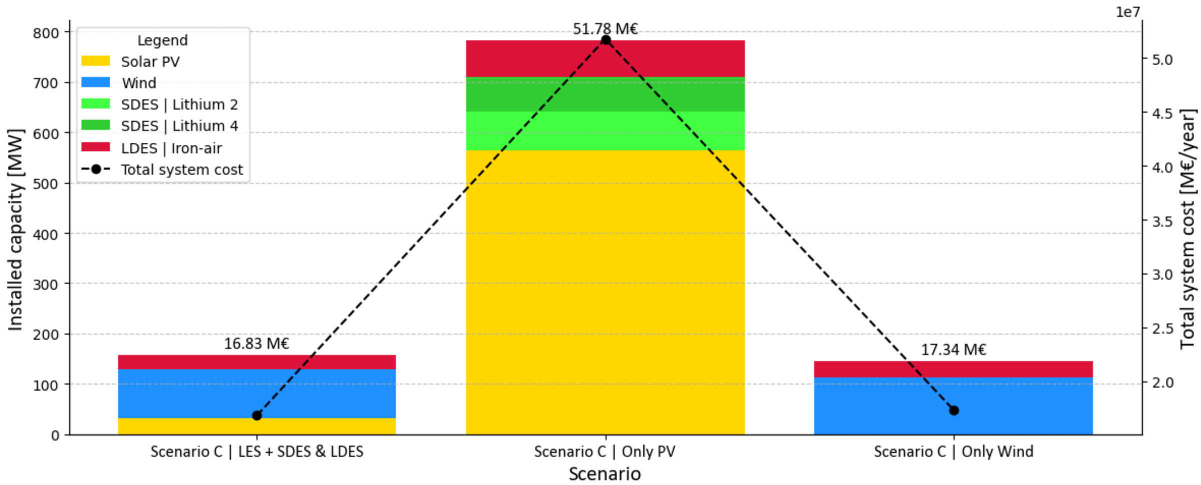

Figure 17: Scenario analysis Generation portfolio.

When solar is the only available RES, a total of 565 MW of solar must be installed to meet the 20 MW of chemical demand. To bridge periods of low REG, the model deploys a combination of lithium-LFP (2h and 4h) and iron-air storage. This configuration results in the highest system cost, at €51.78 million/year. In the wind-only scenario, 112.3 MW of wind capacity is deployed, supported by 32.4 MW of LDES, leading to the lower system cost of €17.34 million/year. Compared to these restricted cases, the original scenario C, which allows optimization over both REG and ESS technologies, results in a more balanced configuration with more balanced capacity and the lowest overall cost (€16.83 million/year).

This analysis demonstrates that combining both wind and solar leads to the most cost-effective LES within the given model constraints. Relying solely on solar requires significantly more REG and ESS capacity, which increases total system costs. In contrast, scenarios that include wind generation, either exclusively or in combination with solar, result in more efficient and cost-effective outcomes. The results show that wind has the biggest contribution in lowering system costs and with less required ESS. This is because wind generation is more stable over time and better aligned with the constant electricity demand of chemical processes. Solar, on the other hand, follows a pronounced daily cycle and suffers from complete generation drop-offs at night and during multi-day low irradiance periods. As a result, the system must compensate for these gaps using LDES and SDES. This leads to higher investment costs and system oversizing. These findings underscore that wind is inherently more compatible with continuous chemical demand in LES.

5.2 Fluctuated demand

The second sensitivity analysis conducted focuses on the demand profile. Since the chemical processes is characterized by very stable demand, alignment with intermittent REG is even more challenging and requires ESS. However, to get a better understanding of the behaviour of different ESS it is interesting how the optimal ESS configuration changes when demand becomes more volatile. To simulate this a randomization tool is applied which adjusts the 20MW constant demand towards more volatile profiles based on the following influences:

1. **Daily cycles** | Captured via a sine wave with a 24-hour period to represent typical intra-day operational fluctuations.
2. **Weekly patterns** | Modelled using a second sine function with a 168-hour (7-day) period to simulate lower weekend activity.
3. **Random noise** | Small random perturbations were added to introduce natural irregularities in industrial behaviour.

These adjustments are performed at two intensity levels, meaning (1) variations between 15 and 25 MW and (2) variations between 5 and 35MW. The average of total adjusted demand remains an annual average of 20MW to secure comparability with the initial flat demand of the case in scenario C.

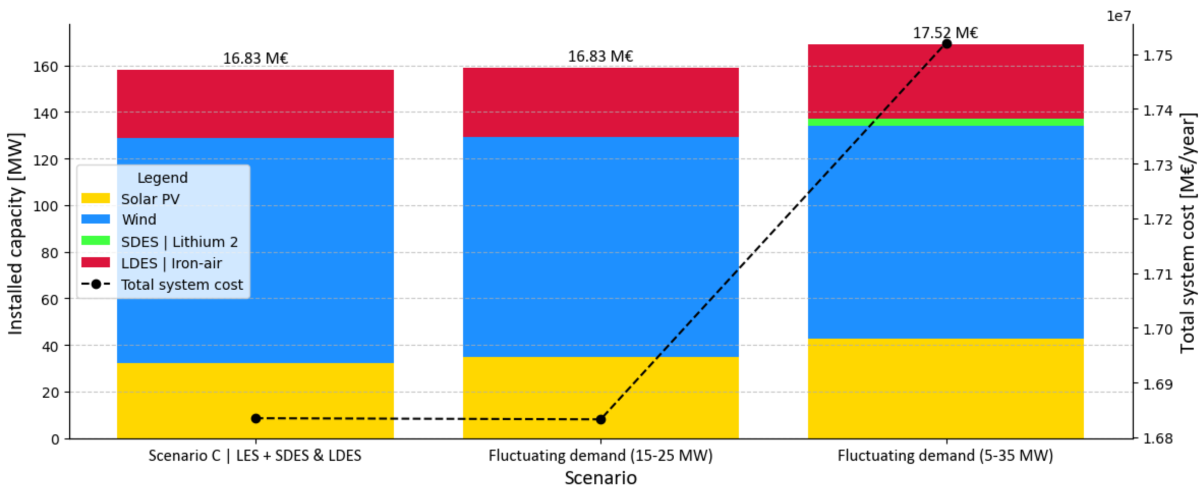

Figure 18: Scenario analysis Demand adjustments.

As shown in Figure 18, the introduction of demand fluctuations has a modest impact on both the optimal system configuration and total system cost. Moderate variability (15–25 MW) has negligible effects compared to the flat-demand scenario C. However, more intense fluctuations (5–35 MW) lead to a noticeable shift: the model installs additional solar, LDES, and also SDES capacity to manage rapid demand peaks. This results in an annual system cost increase of over €0.7 million (+4.1%). These findings indicate that under highly variable industrial demand, SDES becomes cost-effective as part of a hybrid ESS solution. This underscores the importance of accurate demand profiling in LES planning and highlights the role of SDES in accommodating operational flexibility. The corresponding dispatch profiles are included in Appendix F.

5.3 SDES price reduction

The final part of the sensitivity analysis examines the impact of reduced capital costs for SDES, represented by lithium-LFP batteries. While lithium has already seen significant cost declines, further reductions are expected due to economies of scale and technological advancements (IRENA, 2024). To quantify the impact of lower SDES costs on the overall system configuration, a sensitivity range was introduced with stepwise reductions in lithium CapEx from 100% to 50%, in 10% intervals.

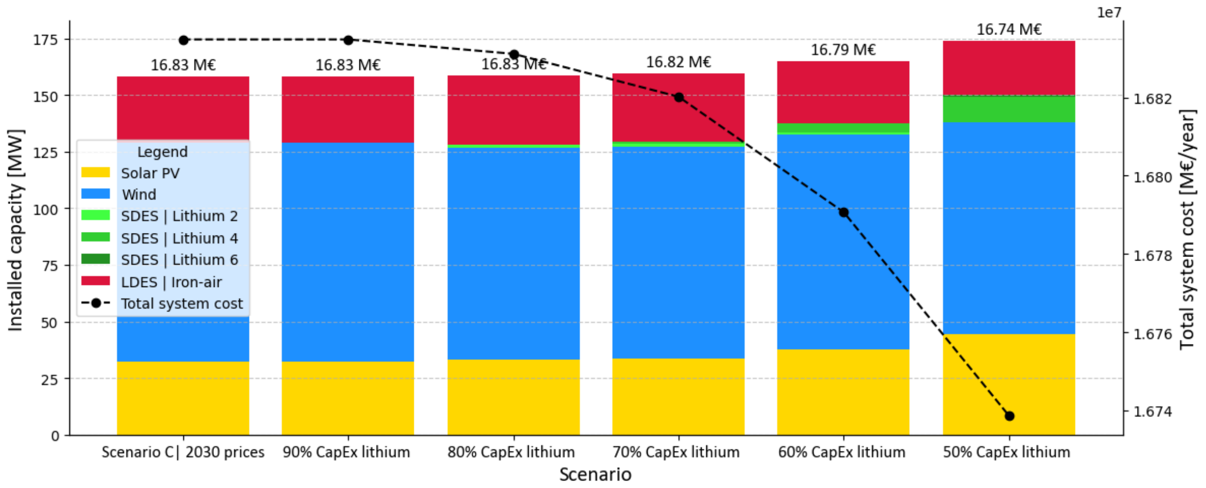

Figure 19: Sensitivity analysis SDES CapEx reduction.

The results as shown in Figure 19 demonstrate a clear trend in the optimal storage mix and total system cost as lithium becomes cheaper. Initially, at 2030 price levels (100%) and at 90% CapEx, only iron-air (LDES) is installed, with a capacity of 29.3 MW. No SDES is selected. However, as lithium prices drop further SDES deployment increases:

- At 80% CapEx, SDES begins to appear with 1.44 MW of Lithium 2hr storage and a minor deployment of Lithium 4hr (0.02 MW). Interestingly, LDES deployment is increased with 3.5% up to 30.3MW.
- At 70% CapEx, both Lithium 2hr (1.4 MW) and 4hr (0.9 MW) are deployed, slightly displacing LDES (to 30.1 MW).
- At 60% CapEx, a notable increase in Lithium 4hr (4.4 MW) is observed, accompanied by a further reduction of 7,5% in Iron-air (27.1 MW).
- At 50% CapEx, the system installs 10.9 MW of Lithium 4hr and 0.9 MW of Lithium 6hr, while Iron-air drops to 24.2 MW, a total reduction of 17.4% compared to the baseline.

In parallel, the total annual system cost steadily decreases from €16.83 million to €16.74 million, yielding nearly €100.000 in annual savings which represents a 0.56% cost reduction. While modest in absolute terms, this shift indicates the trend: as SDES becomes cheaper, it increasingly displaces LDES in the cost-optimal energy system. These findings confirm that reduced CapEx of lithium-LFP storage not only reduces overall costs but also shifts the cost-optimal configuration toward greater integration of SDES, particularly lithium systems discharge durations of 4 and 6 hours, thereby decreasing reliance on LDES technologies.

6 Qualitative market validation

To complement the techno-economic modelling results, a qualitative market validation was conducted through interviews with two industry experts active in the Dutch chemical sector. The aim was to verify the realism, applicability, and relevance of the model assumptions and outcomes in a real-world industrial context. The interview framework was structured around three core themes: (1) validation of model structure and assumptions, (2) feasibility of LES, and (3) the broader market and policy landscape for industrial electrification. The remainder of this chapter summarizes the main insights.

6.1 Model structure and assumptions

The discussion began with the model structure and assumptions, which mainly focused on the LDES battery feasibility. While technically promising, the practical implementation of iron-air batteries at industrial scale raised concerns. Although promising on paper, these LDES systems have a low round-trip efficiency, implying a substantial energy loss of around 55%. This study does not analyse the underlying chemical processes in detail or determine the exact cause of these losses (e.g. thermal, mechanical, or electrochemical). However, at a 20 MW scale, a considerable portion of this loss in the form of heat would likely require forced cooling, bringing additional practical challenges. The experts emphasized that passive air cooling may be insufficient and water availability near chemical sites is often limited. These operational constraints require attention, although they are not included in the current model.

The experts explained that, based on their assessment, currently available ESS technologies (both SDES and LDES are not yet deemed suitable for large-scale chemical production due to insufficient discharge rates and storage volumes. Prior internal assessments of thermal energy storage led to similar conclusions, showing that the continuity and scale of chemical production currently exceed what battery systems can support.

6.2 Feasibility of local energy systems

Regarding the comparison between grid expansion and a LES, the experts emphasized the need for caution due to potential cost imbalances. The evaluation of the LES in this research excludes several cost components, such as on-site electrical infrastructure (e.g., cabling between REG assets), land use, and permitting procedures. In contrast, the base case for grid expansion includes full contractual and consumption-related costs.

Additionally, while grid expansion is costly, the expert emphasized that it also provides regional benefits by increasing capacity for multiple stakeholders beyond the chemical site. Overall, caution is needed when interpreting the comparison with the base case because the LES scenarios exclude connection and reinforcement costs. It is important to be explicit about these assumptions. Nonetheless, the experts highlighted that the model is valuable for comparing the relative cost-effectiveness and dispatch behaviour of different ESS technologies under consistent boundary conditions. In that sense, the findings support early-stage exploration and innovation in industrial electrification.

Spatial and societal constraints were also highlighted. The model assumes the installation of multiple wind turbines and large solar fields around the chemical site, which is challenging due to limited space and public opposition. One of the experts cited a real-world example in which a wind project faced heavy local resistance, illustrating the real-world difficulty of implementing REG solutions. This illustrates the importance of validating spatial and social feasibility alongside technical and economic parameters.

6.3 Market and policy perspective

From a market and policy perspective, the expert outlined a challenging situation. The current Dutch regulatory environment is considered unfavourable for industrial decarbonisation. Key barriers include high grid tariffs, the national CO_2 taxes, and the absence of energy price compensation measures which are available in other EU countries and non-EU regions.

The IKC (Indirect Cost Compensation) scheme, which aims to compensate energy-intensive industries for energy price increases resulting from the EU Emissions Trading System (ETS), currently does not apply to all types of chemical products within the Netherlands. As a result, these producers face higher indirect CO_2 costs than competitors in other EU countries or non-EU regions with broader compensation mechanisms, further weakening their competitive position and making investments in electrification less financially viable.

Given the unlevelled playing field, LES are not a strategic priority for chemical sites. The experts stressed that competitiveness must precede decarbonization: if companies are not economically viable, they will not invest in sustainability. Without a level playing field, firms are more likely to delay investment, downscale operations, or relocate to more favourable regions. Market and policy developments should therefore focus on restoring competitiveness; only then will companies be in a position to invest in sustainable energy systems.

Finally, the experts noted that ESS may find better application in other sectors, such as data centres. Sectors with more flexible demand patterns could have larger potential in utilizing the benefits of ESS, which makes them better suited for integration with REG and emerging storage technologies.

7 Discussion & Reflection

The overarching goal of this research was to assess the costs-effectiveness of using local REG and ESS to electrify a Dutch chemical plant while reducing reliance on the central electricity grid. To this end, a techno-economic optimization model is developed to explore cost-optimal configurations of Lithium-LFP representing SDES and iron-air as LDES, in combination with variable REG.

The discussion is structured as follows: section 7.1 interprets the key scenario and sensitivity outcomes. section 7.2 reflects on the modelling framework and its methodological limitations. section 7.3 discusses the real-world feasibility of LES deployment and outlines implications for policy and other sectors.

7.1 Reflection on the results

7.1.1 No additional value in Hybrid ESS solutions

The three scenarios evaluated within this study demonstrate that the choice between SDES, LDES, or a hybrid configuration fundamentally changes the operation of a LES. In the SDES-only configuration, curtailment is the highest (63%), particularly for solar power, because expanding lithium-LFP battery capacity is to expensive to buffer multi-day mismatches between REG and constant industrial demand. In contrast, the LDES-only scenario reduces curtailment (43%) and renewable oversizing, as LDES allows surplus energy to be shifted across several days. In the hybrid scenario C, the model allows for both ESS-technologies to be deployed, yet consistently selects only iron-air LDES. This indicates that under the modelled constraints, a hybrid configuration does not yield additional value compared to a single LDES solution.

These results are partly consistent with the literature but also highlight important differences. Guerra, (2021) stresses that LDES is essential in high-renewable systems because SDES cannot address multi-day or seasonal gaps. The findings within this study confirm this conclusion in the context of chemical electrification, where continuous inflexible demand amplifies the value of LDES for bridging the gap with intermittent REG. At the same time, López-Ceballos et al., (2025), show that hybrid-ESS can reduce costs in the built-environment by combining the high efficiency of lithium-LFP for peak shaving with the low capacity costs [€/kWh] of thermal batteries for baseload supply. These environments typically experience greater demand volatility, lower power requirements, and benefit from the fast response characteristics of SDES. In contrast, the hybrid configuration with SDES and LDES combined did not offer any additional value in this study, precisely because the continuous and inflexible demand of the chemical industry does not align with intraday balancing or short-duration power support, which limits the role SDES can play in a hybrid setup. This divergence underscores that the cost-effectiveness of hybrid-ESS systems within a LES is highly context-dependent.

The findings also resonate with (Schmidt & Staffell, 2023), who emphasize that the value of storage cannot be assessed in isolation but depends on its integration within the entire energy system including parameters such as: variable REG portfolios, demand profiles, and market structures. While (IRENA, 2024) highlights the rapid cost decline of SDES, the results of this study illustrate that even further reduced SDES costs alone do not resolve the structural mismatch in terms of SDES discharge duration to align with constant industrial demand. Without adequate LDES or demand flexibility, additional REG capacity translates into curtailment rather than usable supply.

Academically, this analysis adds nuance to the ongoing debate on ESS strategies for decarbonization. Lithium-LFP batteries perform well where demand is flexible or variable, but fail to add value when coupled to inflexible, continuous chemical demand. LDES, by contrast, becomes essential in such contexts, not because it is inherently superior, but because it is aligned with the temporal characteristics of chemical demand profiles. Additionally, rather than indicating that hybrid ESS are always ineffective, this result highlights that their added value is highly context specific. For systems with stable, inflexible demand profiles, combining SDES with LDES may introduce unnecessary capital costs without improving operational resilience. As such, the potential of hybrid ESS should be evaluated on a case-by-case basis, with particular attention to the temporal structure of energy demand and the alignment with REG. The model developed in this research is well-suited for such analyses: its modular structure allows for easy adaptation to other sectoral environments, energy demand profiles, or REG mixes. This makes it a useful tool for exploring optimal ESS configurations under diverse technical and economic conditions.

7.1.2 Theoretical LDES dominance

While the previous section 7.1.1 outlined the advantage of hybrid ESS (combining SDES & LDES) on system-level performance in chemical applications, this section discusses the interpretation of the findings on a technology-level. The model outcomes consistently identify iron-air LDES as the most cost-effective ESS across all LES scenarios. This dominance is primarily attributed to LDES's low energy-specific capital cost (€20/kWh), which enables affordable long-duration storage. In Scenario B and C, the system solely installs 29.3 MW of iron-air LDES, confirming its superior performance in aligning REG with the constant industrial demand of a 20 MW e-boiler. The high utilisation of wind power, reflected in the low curtailment ratios in Scenario C, demonstrates LDES's ability to reduce REG curtailment and avoid excessive oversizing of REG. In comparison to SDES, LDES more effectively distributes renewable surpluses over extended periods, thereby avoiding the need for solar as a backup.

However, it is important to note that iron-air batteries are not yet deployed at large scale in industrial applications. Their promising theoretical performance, including energy capacity and efficiency, must still be validated under large-scale operational conditions. The assumed values for efficiency, cost, and discharge duration of iron-air batteries are derived from early-stage projections and laboratory-scale experiments (Brown et al., 2018; FormEnergy, 2023).

This contrasts with lithium-LFP SDES, which is already commercially available and widely applied across various storage use cases. Literature generally identifies lithium-LFP as the dominant storage technology, especially in short-duration, high-cycling environments (IRENA, 2024; Nguyen & Tamrakar, 2024; Schmidt & Staffell, 2023). However, the fact that SDES is not deployed in any of the modelled LES scenarios in this research therefore deviates from current industry trends. This finding resonates with Guerra (2021), who stresses that LDES becomes essential in systems with high REG penetration, as SDES technologies are unable to cope with multi-day variability, continuous inflexible demand of industrial e-boilers. While industry deployment currently favours lithium-LFP, the dominance of LDES in this study illustrates that sector-specific demand characteristics can accelerate the relevance of LDES technologies in practice. It underlines the importance of aligning storage type with the specific operational context and use case.

7.1.3 Base case comparison

The base case scenario provides the costs of grid expansion by including all relevant costs associated with contractual expansion and electricity procurement from the day-ahead market. In contrast, the LES scenarios focus solely on on-site REG and ESS, omitting several real-world cost components that would likely arise in practice and could influence the trade-off. These include:

- Internal cabling and infrastructure between REG, ESS, and demand
- Land availability and spatial planning for wind turbines and solar panels
- Permitting procedures and potential public opposition

- The fact that grid expansion typically provides regional benefits, yet in the model, it focuses on a single chemical site

In addition, for the base case, the electricity prices used to calculate grid procurement exclude VAT, taxes, and levies, and reflect only the market-clearing outcome of supply and demand. Based on the performed expert interviews, it is assumed that large industrial consumers in the Netherlands purchase electricity directly from the wholesale market and therefore face prices close to day-ahead values.

As a result, the cost comparison between the base case and LES scenarios are not entirely balanced. While the optimal LES scenario appears cost-competitive, achieving a total system cost 1.5% below the grid expansion case, this outcome is contingent on the scope of included costs. The model is therefore most appropriate for comparing different ESS under internally consistent assumptions, rather than for making comprehensive claims about the economic superiority of LES over grid-based solutions. Therefore, the observed cost advantage of LES in the model should be interpreted with caution, especially when translating to real-world investment decisions.

7.1.4 Flexible demand

One of the core challenges in designing LES is bridging the temporal mismatch between intermittent REG and continuous industrial energy demand. Schmidt & Staffell, (2023) emphasise that as variable REG penetration rises, the need for flexibility grows exponentially. They identify demand-side response as one of the most cost-effective options to address this challenge. The results within this study confirm this dynamic: the year-round dispatch profile of scenario B (see Figure 20) shows that the iron-air battery's SoC rarely exceeds 40% and is fully discharged only once during the year around November. Because the model assumes zero demand flexibility, this rare multi-day wind scarcity forces the installation of 96.5 MW of wind capacity and extensive storage, even though these assets remain underutilised during the rest of the year. The entire LES is intentionally oversized to cope with this single prolonged wind-scarcity event, leading to over-investment in both REG and ESS capacity which increases REG curtailment and reduces the LES cost-effectiveness.

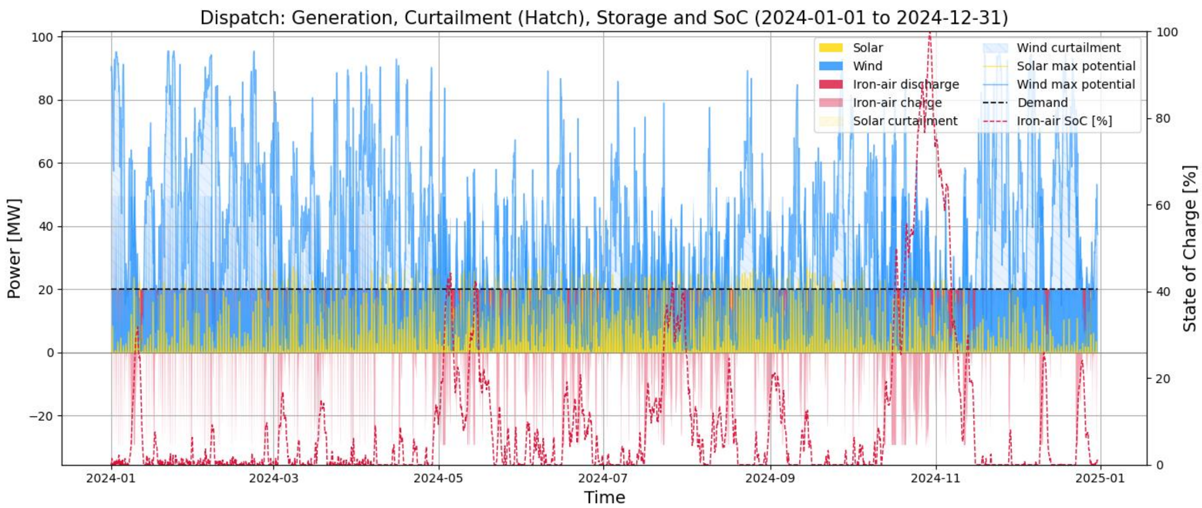

Figure 20: Full year-round dispatch profile scenario B

The expectation is that introducing even minor demand flexibility could therefore drastically lower the LES costs. If the e-boiler is temporarily curtailed only during this single REG-shortage in November, the need for oversized REG and ESS would decrease substantially, allowing for a smaller and more cost-effective LES. In practice, this could mean temporarily reducing e-boiler output or relying on thermal buffers during low-wind periods, without undermining process continuity.

Yet, Chemelot, (2024) and the performed expert-interviews, highlight why such flexibility is difficult to realise. In practice, enabling demand flexibility in the chemical industry is particularly challenging. Production processes are highly interconnected: one plant often supplies feedstocks, steam, or other utilities to another. This tight coupling means that even short interruptions in electricity or steam supply can escalate through the entire cluster, leading to product quality issues, safety risks, and high costs from unplanned downtime and restart procedures. As a result, the potential for demand response is far more constrained than in less integrated sectors. These barriers limit the extent to which demand response can be implemented, even if the economic incentives are strong.

Academically, the contribution of this study is that it quantifies optimized LES system costs under the assumption of perfectly inflexible demand. Literature finds that short-duration storage can often suffice when demand is flexible (López-Ceballos et al., 2025); however, my results show that in interconnected industrial contexts this is not the case, because SDES cannot bridge multi-day mismatches. Instead, LDES becomes essential as long as chemical demand flexibility is absent. This implies that future research should not only focus on improving storage technologies, but also on exploring realistic pathways for enabling controlled flexibility in chemical processes. Where flexibility can be achieved, LES configurations may be significantly smaller and more cost-effective with reduced optimized LES system costs. Where flexibility cannot be achieved, LDES remains the only viable option.

7.2 Reflection on research approach

7.2.1 Scenario design and model Interpretation

The scenario design in this study distinguishes between a grid-expansion base case and three LES scenarios (A, B, and C), which differ in terms of the allowed storage technologies. This structure enabled a controlled comparison of the ESS configurations under identical demand and REG profiles.

A notable outcome is the comparison between Scenario B (LDES-only) and Scenario C (SDES + LDES). Both resulted in identical installed capacities and equal system costs, yet their dispatch behaviour diverged. This divergence does not reflect differences in input assumptions but arises from the decision-space structure of the optimisation. In mixed-integer, time-coupled models such as PyPSA, the presence of additional technology options (even if not selected) can influence solver trajectories which could lead to multiple feasible dispatch profiles for the same LES configuration.

This links to an important structural feature of the model: there is no built-in preference between curtailing solar or wind, and between directly consuming renewable electricity or first storing it in the battery. These choices are left entirely to the optimisation solver. As a result, the model may identify several equally cost-optimal dispatch trajectories for the same LES configuration as demonstrated by scenarios B and C. While these different dispatch profiles do not affect the overall cost-effectiveness results in this study, it highlights that dispatch profiles are not uniquely determined by the techno-economic inputs alone. For future research, it may be interesting to introduce additional constraints or operational preferences for example, prioritising direct use of REG before charging storage or including curtailment penalties. Such refinements would keep the ESS available for other services, such as arbitrage or ancillary markets, and could yield more realistic system operation pathways.

This observation underscores the importance of carefully interpreting model outcomes within the context of solver behaviour and decision space structure. It also reinforces the need for transparency when drawing conclusions from such optimisation results, especially when the operational characteristics of non-selected technologies indirectly shape the system dispatch.

Compared to alternative frameworks reviewed in section 3.2.2, the choice for PyPSA was deliberate. Its open-source structure, transparent optimisation formulation, and strong capabilities for investment-dispatch analysis make it well-suited for techno-economic ESS comparisons. However, unlike GAMS-based models, PyPSA does not natively incorporate multi-sector integration, contractual constraints, or behavioural rules. In addition, it also does not allow process-level dynamics as tools such as Aspen Plus or gPROMS offer. This means that the results in this study are best interpreted as internally consistent relative comparisons between LES configurations, rather than as unique forecasts of in-depth chemical process operation.

Finally, the perfect foresight assumption embedded in PyPSA further shapes results: by knowing in advance when prolonged scarcity events occur, the solver naturally favours long-duration solutions such as LDES. In reality, such foresight is never available. Forecasting errors mean that operators do not know exactly when a multi-day scarcity will begin, how long it will last, or when recovery will occur. This implies that LDES is less “perfect” in practice than in the model: storage might be discharged too early, leaving insufficient reserves for the remainder of the scarcity, or too late, missing opportunities to cover deficits. Under these conditions, the relative value of SDES and demand-side flexibility increases, as they provide resilience against near-term uncertainty and forecast errors. Therefore, while the modelled dominance of LDES is robust under perfect foresight, its magnitude may be overstated when extrapolated to real-world settings.

Academically, this illustrates that optimisation outcomes are shaped not only by techno-economic input parameters but also by solver behaviour and modelling framework design. For the debate on LES, this means that conclusions about the dominance of a given technology should always be cross-validated with alternative modelling approaches and assumptions. In this way, the findings of this study contribute to a more nuanced understanding of when LDES dominance is robust, and when it may be an artefact of the modelling framework.

7.2.2 Sensitivity analysis: Design and justification

The sensitivity analysis in this study was not intended to provide an exhaustive exploration of parameter uncertainty, but to assess whether the main findings on ESS configurations remain valid under alternative but plausible conditions. This is essential, because optimisation results are always conditional on input assumptions, and conclusions about technology dominance (e.g. LDES over SDES) can easily be artefacts of one particular setup.

The three tests therefore targeted the parameters most likely to shift the balance between storage technologies: (1) the generation mix, (2) the volatility of chemical energy demand, and (3) the investment cost of SDES. Together, these cover both external uncertainties (e.g. technology cost trajectories) and decision levers (e.g. REG configuration), following the XLRM framework (Lempert et al., 2003).

The results show that the core conclusion (that LDES dominates under stable industrial demand) is robust across a wide range of assumptions. Even under more solar-heavy mixes or moderate demand variation, the system continues to favour LDES. However, the sensitivity analysis also reveals boundary conditions where this conclusion may no longer hold. When demand becomes highly volatile, SDES enters the cost-optimal mix to provide short-duration flexibility. Likewise, when SDES costs decline significantly, it becomes competitive only in conjunction with volatile demand. These outcomes are important because they highlight that the dominance of LDES in this study is not absolute, but conditional on the assumption of perfectly stable demand and current cost levels.

This interpretation adds nuance to the broader discussion on modelling robustness. Without sensitivity testing, the results might suggest a deterministic conclusion (LDES always dominates). The sensitivity analysis demonstrates instead that demand characteristics and cost trajectories are critical tipping points. Academically, this underscores the need to treat optimisation results as scenario-dependent insights rather than forecasts. For industry, it signals that investment strategies should remain adaptive: LDES is essential where demand is fixed, but in more flexible demand contexts or with declining SDES costs, hybrid solutions may emerge as more cost-optimal solutions.

7.2.3 Model limitations

To ensure feasibility within the limited time of this research, several simplifying assumptions were made. While these enable consistent comparisons between scenarios, they also reduce the model's predictive validity for real-world implementation. The key limitations are summarised below:

Structural simplifications | The model assumes perfect foresight, fixed storage efficiencies, and excludes start-up/shutdown dynamics. PyPSA is electricity-only and does not capture sector coupling with thermal systems or hydrogen. These assumptions simplify the problem but bias results towards long-duration solutions: as explained in 7.2.1 perfect foresight makes it easier for the model to size and deploy LDES optimally, while the absence of sector coupling underestimates the potential role of thermal integration or hydrogen as flexibility options. Furthermore, spatial, and regulatory constraints, such as land availability, permitting, or public acceptance, are not represented.

Limited cost scope for LES configuration | To maintain modelling tractability, several implementation costs were excluded in the model. While these are not expected to affect the internal LES scenario comparisons, they may impact the absolute viability of LES in real-world settings. For a detailed discussion of base case versus LES completeness, see section 7.1.3.

Single-year weather data | The model relies on hourly profiles for 2024 only. This restricts robustness, as additional weather years with different weather variabilities could result in different ESS capacities. Consequently, the LDES-dominance observed here may not be equally strong under multi-year variability. Future work should simulate multiple years to assess configuration stability under varying renewable conditions.

Electricity price assumptions | For the grid-expansion base case, electricity procurement costs were based on day-ahead wholesale market prices published by Entso-E, (2025), excluding VAT, taxes, and levies. Expert interviews confirmed that large industrial consumers in the Netherlands typically purchase electricity directly from wholesale markets, making this assumption plausible. However, total system costs for grid expansion are sensitive to these price inputs and may therefore affect the trade-off between LES and grid expansion. Dynamic pricing or long-term contracting was not included. Likewise, alternative power contracting schemes such as TenneT's ATR85/15 flexibility contract were excluded, when this flexibility promoting contract is applied with more flexible demand, as described in section 7.1.4 they may significantly improve the economics of ESS or justify ESS without on-site REG.

Omitted tariff dynamics | Grid expansion costs in the base case are assumed from TenneT tariffs from ACM, (2024). However, TenneT's 10-year forecast anticipates a 53% increase in HS-net tariffs by 2034, or approximately 4.3% per year (TenneT, 2024c). These escalating costs are not accounted for in the current model and may tilt the economic balance further in favour of LES. By investing in a LES, companies not only reduce dependency on grid tariffs, but also gain greater control over future operational costs, making their energy strategy more robust against policy-driven price fluctuations.

No representation of ESS arbitrage or grid services | The model does not capture business cases where storage systems provide value beyond local balancing such as energy arbitrage, congestion relief, or participation in flexibility markets. While section 7.1.4 discusses flexibility on the demand side, this limitation relates specifically to the unrealised revenue potential of ESS assets in broader market participation.

Despite these simplifications, the model was deliberately designed for transparency and modularity. The primary contribution of this approach is not to forecast exact system costs, but to provide a structured comparison of storage strategies under clearly defined assumptions. The limitations identified above underline that the conclusions should be interpreted as relative insights into the techno-economic performance of SDES and LDES, rather than absolute predictions of LES feasibility versus grid expansion. It serves as a decision-support tool that allows users to explore techno-economic trade-offs under clearly defined conditions. The modular structure enables easy adaptation to other load profiles, technologies, or policy regimes, making it valuable for further research and scenario evaluation.

7.3 Practical and policy implications

7.3.1 Applicability in practice

While this study demonstrates that a LES combining wind, solar, and iron-air storage can provide a theoretically cost-effective pathway for electrification, expert interviews and chemical energy strategy publication such as the CES of Chemelot, (2024) revealed that practical implementation remains uncertain. Several real-world barriers were identified that fall outside the scope of the model.

Chemical processes are not typically working as an isolated plant but function within one cluster of interconnected systems optimised for continuous operation. They exchange utilities and by-products, therefore any disturbances in one unit escalates quickly across the site. This means any electrification adjustments to the process affect the existing cluster. Chemelot, (2024) notes that once operational experience is gained, a small amount of demand flexibility can be unlocked from existing installations, while future units are expected to be designed with greater flexibility. This indicates that in the near term, cluster-wide demand response is feasible but remains limited compared to total site demand.

On the other hand, one of the most pressing challenges for LES deployment is spatial feasibility. Deploying megawatts of REG capacity near or within industrial clusters is constrained by limited available land and competing land-use interests. In addition, interviewees highlighted issues related to public opposition, particularly regarding large-scale wind projects, and the complexity of permitting procedures, which can delay project development.

On the technical side, the model excludes infrastructure-related costs as outlined in section 7.1.3, all of which contribute to real-world implementation costs. Moreover, concerns were raised about the scalability of LDES technologies. As explained in section 2.3, iron-air batteries, although promising on paper, have not yet been deployed at industrial scale, meaning that their modelled performance and cost assumptions are largely based on laboratory-scale projections and early-stage estimates.

In summary, the LES configurations proposed in this study should be interpreted as conceptual explorations rather than immediately actionable investment cases. Real-world applicability will depend on the following factors that must be carefully considered before deployment: detailed site-specific assessments, public and regulatory acceptability, and technological maturity.

From an academic perspective, the focus should lie not on treating modelling results as predictions, but on understanding the boundary conditions under which certain ESS appear cost-effective. This study illustrates that conclusions about LDES dominance, hybrid ESS value, or the competitiveness of LES against grid expansion are highly dependent on assumptions about demand flexibility, technology maturity, and spatial feasibility. Future research should therefore emphasise developing frameworks that integrate above mentioned real-world constraints into system models, so that results reflect not only techno-economic optimisation but also the conditions that shape practical feasibility.

7.3.2 Policy landscape

Despite the technical feasibility and potential cost-effectiveness of LES, the current Dutch policy framework creates significant barriers to their practical adoption. Experts indicated that the current tariff structure discourages electrification, particularly for industrial sites facing high grid tariffs and limited compensation for flexibility or local REG.

Industry experts highlighted the absence of supportive market conditions as a major barrier. Unlike neighbouring countries, Dutch policy currently offers limited compensation for rising energy costs and imposes high grid tariffs and CO_2 taxes. As a result, LES deployment is not a strategic priority for chemical companies today, who emphasise that financial viability must come before decarbonisation.

Additionally, rising grid tariffs as explained in section 7.2.3 introduce long-term financial uncertainty. These projected increases are not included in the base case analysis of this research, potentially underestimating the future costs of grid-based solutions. By contrast, deploying a LES can (partially) mitigate this risk by reducing dependency on external grid tariffs and disconnecting the site from unpredictable network cost developments.

Overall, the chemical policy environment remains misaligned with the energy transition ambitions for Dutch industry. While a LES can offer technological and economic benefits, its adoption will require a more favourable regulatory landscape, one that recognises and rewards flexibility, local REG, and the avoidance of grid expansion. Without such reforms, industrial decarbonisation efforts may remain constrained despite the availability of technically viable solutions.

Academically, it is interesting to analyse not only the technical or cost-optimal designs of LES, but also the institutional frameworks that determine whether such designs can become cost-effective in practice. This study suggests that without the inclusion of supportive tariffs and compensation mechanisms, the value of LDES or hybrid ESS remains largely theoretical. For research, this implies that techno-economic modelling of chemical decarbonisation strategies should be coupled with regulatory and market design perspectives, so that conclusions about cost-effectiveness are grounded in both engineering and policy realities.

7.3.3 Comparison to other Sectors

The model outcomes of this study are most applicable to the chemical industry, which is characterised by high, continuous energy demand without demand variability. This makes the results particularly relevant for baseload industrial processes such as steam production and feedstock conversion.

At the same time, the modelling approach as explained in section 3.2.3 and 7.2.3 of this research is deliberately designed to be modular, transferable and reproducible. The model allows all key inputs such as: demand profiles, technology costs, and REG data, to be substituted without altering the underlying structure. As a result, the model is ready to be adapted for different chemical plants, industrial clusters, other storage technologies or even other sectors such as steel or datacentres and food processing. Each of these contexts has distinct demand patterns (from continuous, to variable and flexible), which means the same modelling approach can be used to assess whether the dominance of LDES persists, or whether hybrid ESS configurations become more attractive. If the generated insights hold in other sectors depends on the temporal characteristics of their demand profiles.

Academically, this highlights the dual value of the work: the results provide sector-specific insights for the chemical industry, while the methodological approach offers a broadly applicable tool for exploring local energy systems across industries and geographies. For policymakers and researchers, this means that the conclusions drawn here are not confined to a single case-study, but illustrate a generalisable method to evaluate the techno-economic viability of LES under varying structural conditions.

8 Conclusion & Recommendations

This chapter provides the conclusions on the research questions within this master thesis. The research examined the costs-effectiveness of using local REG and ESS as an alternative to grid expansion for the electrification of a Dutch chemical plant. By combining techno-economic optimization using the PyPSA framework with expert interviews and literature insights, this study assessed how different storage configurations, renewable energy sources, and system constraints affect the feasibility and cost-effectiveness of a LES.

The chapter begins by answering each of the sub-questions in a structured manner, followed by a synthesized conclusion addressing the main research question. The concluding section presents recommendations for future research, highlighting potential model extensions and broader applications across different sectors and contexts.

8.1 Answer to sub-research questions

SQ1 | Which chemical processes are considered electrifiable according to current academic literature?

The chemical industry is the most energy-intensive industry within the Netherlands. Approximately 78% of the total chemical energy demand is dedicated to thermal processes, decarbonizing this demand via PtH applications is frequently considered as key strategy to fulfil climate targets. Processes requiring low- and medium-temperature (up to 600°C) heat are considered highly suitable for electrification with the following PtH technologies selected as most promising ones:

1. E-boilers,
2. Industrial heat pumps,
3. Mechanical Vapour Recompression (MVR).

These technologies are commercially available, but their operation range varies in both temperature and power output. Among the available technologies, the e-boiler most closely matches the operating characteristics of conventional gas-fired boilers. With a Technology Readiness Level (TRL) of 9, they are commercially available at industrial scale, reaching capacities up to 90 MW, operating temperatures of 600°C, and pressures as high as 150 bar. Their efficiency approaches 99%, making them ideal candidates to replace gas-fired steam systems (Ouden et al., 2017).

However, despite their technological maturity, widespread adoption of the e-boiler is limited by the high costs associated with grid connection, capacity tariffs, and elevated electricity prices (Madeddu et al., 2020). In conclusion, within the assessed literature steam production and other low- to medium-temperature thermal processes in the chemical industry are considered as highly electrifiable, with e-boilers, heat pumps, and MVR identified as the most viable technologies to enable this transition.

SQ2 | What storage systems are available to fulfil the energy demand of electrifiable chemical processes according to academic literature?

Academic literature identifies five main categories of ESS: mechanical, thermal, electrical, electrochemical, and chemical. Among these, electrochemical and thermal storage are considered most relevant for supporting the electrification of industrial chemical processes, given their scalability and compatibility with electricity-based systems. This research focuses on two representative electrochemical technologies:

1. Lithium-LFP batteries, representing SDES,
2. Iron-air batteries, representing LDES.

These technologies are selected because they reflect both the current commercial standard (SDES) and the most promising emerging solution (LDES) for industrial-scale energy storage under varying duration requirements.

Lithium batteries are the commercially dominant SDES technology, typically used for intraday balancing with discharge durations up to six hours. Their high roundtrip efficiency (~95%) and high-power density make them well-suited for peak shaving and short-term flexibility. However, the energy capacity cost [€/kWh] remains relatively high due to the use of scarce materials. This makes them less cost-effective for long-term storage, as scaling the energy capacity [kWh] would lead to disproportionately high investment costs.

Iron-air batteries, in contrast, are still in development (TRL 4–5), but are the most promising for industrial-scale LDES. They rely on abundant, low-cost materials (iron and air), resulting in energy capacity costs as low as €20/kWh, approximately nine times lower than lithium. This makes them much more cost-effective for storing large energy volumes with discharge durations of up to 100 hours. However, they are characterized by a lower power density [kW] and have a roundtrip efficiency of only 45%, which makes them less suitable for short-term response, as their low power output [kW] limits their ability to deliver large amounts of energy [kWh] in a short period.

Given the complementary characteristics of SDES and LDES, hybrid storage systems that combine both technologies have emerged as promising solution in other sectors. These configurations benefit from the high efficiency and high power of SDES, combined with the cost-effective, energy storage capacity of LDES. Although initially demonstrated in the built environment, this research explores their applicability within the industrial context of the Dutch chemical sector. Unlike the built environment, the chemical industry is characterized by continuous, high-power energy demand and limited operational flexibility, making the requirements for ESS fundamentally more demanding in terms of reliability, duration, and scale.

In short, this research focuses on lithium-LFP and iron-air batteries as representative storage technologies, selected for their complementary strengths: lithium-LFP provides high efficiency and fast response over short durations (SDES), while iron-air enables low-cost, with long-durations (LDES) at scale. Although fundamentally different in design and performance, combining the principle of SDES and LDES into a hybrid ESS has proven to be promising in other sectors. Such hybrid configurations offer a strategic advantage by addressing both intraday variability and multi-day supply shortages and are therefore considered a promising solution to meet the continuous and inflexible energy demand of electrified chemical processes.

SQ3 | Which evaluation criteria are relevant for comparing Energy Storage Systems technologies in chemical applications?

To properly evaluate ESS within chemical applications, this study applies a multidimensional framework that combines literature insights, expert interviews, and a model-based analysis. The relevant evaluation criteria start by explaining the technology-level parameters followed by system-level performance indicators:

Technology-level parameters, derived from the literature review and expert validation, which inform the model inputs and reflect the technical and economic characteristics of SDES and LDES.

1. **Energy capacity costs [€/kWh]** | Represent the investment needed to scale the energy volume of a storage system. This cost is mainly determined by the storage medium and is a critical metric in ESS comparison, particularly for the chemical industry, which demands large, continuous energy supply over extended periods.
2. **Power capacity costs [€/kW]** Reflect the cost of delivering energy at a specific rate and are influenced by power electronics and the electrochemical reaction speed. Slow reaction kinetics require larger active surface areas, increasing component sizing and investment per kW.
3. **Discharge duration [h]** | Indicates how long energy can be delivered at rated power [kW], indicating whether a system is suited for intraday or multi-day balancing.
4. **Roundtrip efficiency [%]** | Measures the ratio of usable output to input energy [kWh] over a full charge-discharge cycle. Lower efficiency increases system losses and operating costs, making it especially relevant when REG is limited.
5. **Lifetime [y]** | Indicates the expected operational duration before significant degradation occurs. It affects long-term investment value and replacement needs.

System-level performance indicators; the following indicators are used in the scenario and sensitivity analysis to evaluate how different ESS configurations affect system-wide outcomes:

1. **Total system cost [€/year]** | The objective function in the model is to minimize total system costs, combining CapEx and OpEx within the given constraints.
2. **Installed capacity [MW]** | Reflects the optimal deployed power capacity of storage units and generators required to fulfil demand under the different scenario limitations.
3. **The curtailment ratio [%]** | A performance indicator that quantifies the average utilization of installed REG capacity over time. It serves in this research to assess how ESS deployment affects the effective use of renewable assets across different LES scenarios.
4. **Dispatch behaviour** | Describes how and when system components such as ESS, and REG, are utilized over time. For ESS, this includes charge/discharge cycles and SoC profiles in response to fluctuating supply and demand.

In conclusion, comparing ESS technologies for chemical applications requires a combination of technology-specific parameters and system-level indicators, to evaluate both the feasibility of individual storage technologies and their impact on overall system performance under industrial conditions.

SQ4 | What is the cost-optimal combination of SDES and LDES to meet a chemical plant's energy demand?

The cost-optimal configuration consists exclusively of 29.3 MW LDES, with 0.0 MW SDES installed. This outcome follows from Scenario C, which allowed combining SDES and LDES. Despite this flexibility, the model optimized identical configuration as Scenario B which was constrained to only LDES, demonstrating the model's preference for iron-air LDES and that lithium-LFP SDES is not cost-effective under the defined technical and economic assumptions.

The resulting total system cost in Scenario C is €16.83 million/year, identical in cost to Scenario B (LDES-only). This represents a 37% reduction compared to Scenario A, which relies solely on SDES deployment with a total cost of €26.60 million/year. This cost gap is primarily driven by differences in cost structure between SDES and LDES and the misalignment of SDES with REG and continuous demand profiles.

The high cost of Scenario A is explained by the need to install 88.2 MW lithium-LFP SDES, which has relatively high power-specific costs (€1092/kW for 6hr discharge) and shorter duration, requiring ESS power capacity oversizing and additional REG power to fulfil the same continuous demand.

In contrast, LDES (iron-air) has low energy-specific costs (€20/kWh), enabling lower-cost for long-duration storage. The identical optimized configuration in Scenario C and B confirms that under current assumptions, hybrid ESS configurations do not offer any cost advantage over LDES-only systems. The capacity deployment in Scenario C was:

- **Wind**: 96.5 MW
- **Solar**: 32.3 MW
- **LDES**: 29.3 MW
- **SDES**: 0.0 MW

In conclusion, the most cost-effective LES configuration with an annualised cost of €16.83 million/year consists solely of 29.3 MW iron-air LDES, as SDES technologies were not selected due to their high power-specific costs at longer durations and limited contribution to lowering system costs or REG curtailment.

SQ5 | How do SDES and LDES compare in their techno-economic performance for electrified chemical processes?

LDES outperforms SDES in techno-economic performance by better matching the temporal characteristics of REG to the continuous electricity demand of chemical processes. This is supported by the dispatch and SoC behaviour observed in the sensitivity and scenario analysis.

While LDES and SDES differ significantly in cost structure, their technical performance, particularly dispatch behaviour and alignment with REG and demand, is the key factor explaining LDES's superior performance in chemical electrification.

In Scenario A, SDES (88.2 MW lithium-LFP) is mainly charged by excess wind (144.4 MW), while solar (21.0 MW) only activates during prolonged shortages of wind. As SDES cannot span multiple days due to its limited discharge duration (6h), its SoC indicates that it is frequently fully discharged during low-wind periods. In these moments, solar serves as a backup REG. However, because SDES replaces most of solar its functional role during sufficient REG, this leads to underutilized solar capacity and a high curtailment ratio of 89.93%. This scenario illustrates that SDES assists wind but cannot eliminate the need for backup REG, which results in configuration inefficiencies and high-curtailment rates.

In contrast, Scenario B demonstrates how LDES (29.3 MW iron-air) enables temporal spreading of wind surpluses with less need for curtailment or backup. The system relies on a smaller installed wind power capacity (96.5 MW) and the LDES shows deep SoC cycles to buffer multi-day REG shortages. Dispatch plots show that LDES charges during windy periods and discharges gradually across multiple days of low wind. This allows the system to operate with lower REG overcapacity and lower curtailment ratios: 48.32% for wind and 1.76% for solar. This illustrates a better alignment between REG, ESS, and demand.

Scenario C confirms this dynamic: although both SDES and LDES were available, only LDES is deployed. This implies that SDES offered no additional dispatch value beyond what LDES already provided, particularly in systems with constant chemical load profiles. However, this changes under fluctuating demand conditions: in the sensitivity analysis, where demand fluctuated intensely between 5–35 MW, SDES is starting to get deployed alongside LDES, indicating that SDES adds value for other demand profiles with more flexibility or short-duration peaks under variable industrial demand patterns.

In conclusion, LDES is techno-economically better suited than SDES for electrified chemical processes, because it enables energy balancing over multiple days, reduces the need for oversized REG, and supports continuous electricity supply. In contrast, SDES lacks the required discharge time and leads to high redundancy and curtailment.

8.2 Answer to the main research question

This section addresses the main research question:

"How do different energy storage duration and renewable generation configurations affect the cost-effectiveness of local energy systems to electrify a Dutch chemical plant facing grid congestion?"

This research suggests that local renewable energy generation and storage can theoretically meet a 20 MW e-boiler load without reliance on the electricity grid, thereby enabling a decentralised electrification pathway for the Dutch chemical industry. The results are derived from a cost-optimisation model developed using the PyPSA framework. Under the defined assumptions, the modelled system costs are competitive with conventional grid expansion. In Scenario C, which allows unrestricted deployment of all REG and ESS technologies, the most cost-optimal LES configuration to satisfy the additional electrical energy demand of 20 MW consists of:

96.5 MW wind, 32.3 MW solar, 29.3 MW iron-air LDES.

This configuration results in an annual total system cost of €16.83 million. Which is 1.5% lower than the grid expansion base case, and 37% lower than the SDES-only scenario. By integrating technology-specific costs, operational constraints, and REG variability, this model provides insights into how these factors affect the optimal configuration, dispatch behaviour, and system costs of the LES. The key findings related to the cost-effectiveness of LES deployment are summarised below.

1. **LDES enables cost-effective system operation under grid constraints**
   Iron-air LDES proves to be the most cost-effective storage technology. Its low energy capacity cost (€20/kWh) facilitates affordable long-duration storage, reducing the need for oversized – or backup REG assets and improving alignment between REG output, storage dispatch, and continuous chemical demand.
2. **SDES increases system cost and curtailment when used alone**
   Lithium-LFP SDES lacks sufficient discharge duration for multi-day balancing. In Scenario A, full discharge during extended wind shortages forces deployment of solar as backup supply to ensure energy supply during wind shortages. Since solar is only required during such rare events, its average utilisation remains low, resulting in a high curtailment ratio of 89.93%.
3. **Hybrid configurations provide no additional value under current conditions**
   In the cost-optimal Scenario C, the model installs only LDES, even though SDES is available, indicating that hybrid ESS configurations do not improve cost-effectiveness under the modelled cost structure and system constraints. Hybrid ESS do not provide additional value over LDES-only.
4. **Storage type determines renewable utilisation**
   LDES enhances renewable utilisation by enabling temporal shifting across multiple days, improving REG integration by at least 20 percentage points compared to the SDES-only configuration. SDES is limited to short-duration balancing and expanding its capacity is to expansive to reach sufficient discharge durations for bridging the gap between REG and continuous chemical demand profiles.
5. **Wind dominates the generation mix due to system cost and reliability**
   In all LES scenarios, wind is favoured over solar in terms of installed power capacity because of its seasonal consistency and stronger alignment with continuous demand. Solar's contribution remains marginal, primarily as backup during SDES depletion events.

The sensitivity analysis reinforces the robustness of these findings by testing variations in key assumptions. It shows that SDES deployment only becomes cost-effective when demand profiles are increasingly more volatile, with fluctuations between 5 and 35 MW, or when its capital expenditure is reduced by at least 20 percent. These results confirm that LDES remains the preferred storage option under stable chemical baseload conditions.

While the model offers valuable insights into techno-economic trade-offs, expert interviews underline the need for caution when interpreting these results in real-world applications. Several feasibility barriers were identified that fall outside the model scope. These include additional cost components for the LES such as internal cabling, and permitting procedures, but also, spatial constraints on industrial sites, and societal resistance to large-scale renewable deployment. Furthermore, the model evaluates LES performance at the individual site level and does not capture potential regional benefits associated with grid expansion, such as regional balancing and shared flexibility.

Therefore, the results should not be interpreted as complete investment cases. Rather, they represent a techno-economic exploration based on a defined set of assumptions, constraints, and system boundaries. Any application to real-world settings requires careful contextualisation, considering site-specific constraints, regulatory frameworks, and broader system interactions that were not included in this research.

From a policy perspective, experts stressed that the current Dutch regulatory environment discourages industrial electrification due to high grid tariffs and limited energy price compensation mechanisms compared to neighbouring countries. Without a more level playing field, companies are unlikely to invest in decarbonization measures. They also noted that ESS may be better suited to sectors with more flexible demand, such as data centres, unless LDES technologies mature.

In conclusion, this research shows that a cost-optimal LES for a Dutch chemical plant can theoretically electrify a 20 MW thermal load without relying on the external grid. The most efficient configuration combines wind, solar, and iron-air LDES, resulting in annual system costs of €16.83 million, which is lower compared to grid expansion or SDES-only deployment. The key benefits of this approach include avoidance of uncertainty associated with tariff developments for grid expansion, improved REG utilisation, reduced curtailment, and lower system oversizing due to LDES's ability to provide long-duration balancing. However, practical implementation requires careful consideration of site-specific constraints and external costs beyond the modelled scope. Thus, while LES offers a viable and cost-competitive pathway for industrial electrification, its real-world feasibility depends on additional contextual and regulatory factors.

8.3 Recommendations for future work

To build on the findings of this research, several directions for future work are proposed. The recommendations build directly on the key findings and limitations of this research. They are structured to first address immediate modelling assumptions, then broaden to uncertainty and sector coupling, and finally extend to technology development and system-wide considerations.

1. Demand flexibility as a design parameter

The present model assumed a fixed and fully inflexible demand profile. This resulted in substantial overinvestment in both REG and storage to cover rare multi-day scarcity events. As explained in section 7.1.4 introducing even minor flexibility could drastically reduce LES system costs. As introduced in section 2.5, a promising addition is the integration of contractual flexibility arrangements such as TenneT's ATR85/15 rule, which allows grid operators to curtail the users electrical loads up to 15% of the time in exchange for substantial tariff reductions. Recent studies indicate that consumers with flexible demand profiles can achieve energy cost savings of up to 65% under such contracts (van Druten, 2024). However, as Chemelot, (2024) highlights, unlocking flexibility in practice is difficult. Future work should therefore explicitly investigate demand-side response within the chemical industry as part of LES design. For example, by exploring partial curtailment strategies or advanced maintenance scheduling aligned with REG scarcity events. Such approaches may fundamentally alter the balance between REG and ESS capacities and shift the role of ESS from passive balancing devices to active enablers of demand-side optimisation.

Lastly, although this study does not explore standalone battery storage without co-located REG, such configurations may provide additional opportunities in systems that are contracted to deliver demand flexibility. This opens up alternative LES designs in which ESS plays a leading role in time-shifting demand to optimize energy cost and grid interaction, rather than merely following production profiles.

2. Inclusion of missing cost components

As discussed in section 6 and 7.1.3, the LES scenarios in this study exclude several important cost elements, such as internal cabling, land acquisition, permitting procedures, and public acceptance. Incorporating these factors in future models would yield more realistic cost comparisons between LES and grid-expansion strategies. Doing so would improve the external validity of techno-economic assessments and provide decision-makers with a more realistic basis to evaluate investment strategies.

3. Weather variability & perfect foresight

The modelling framework relied on 2024 as a single reference year with perfect foresight. This simplification overstates the certainty with which LDES can be deployed. Future research should expand to multi-year weather datasets and include imperfect foresight formulations. This would allow testing whether LDES dominance persists under different weather variations and how SDES and demand flexibility can contribute to resilience against forecast errors.

4. Sector coupling and market integration

This study considered electricity-only balancing and excluded alternative flexibility routes such as sector coupling with heat or hydrogen. This aligns with recent findings, which emphasise that the full system value of ESS often emerges only when coupled with other sectors or market services (IRENA, 2024; Schmidt & Staffell, 2023). This could unlock additional value within the LES by reducing reliance on electrical storage and enhancing flexibility. Similarly, storage assets were not allowed to participate in arbitrage, ancillary services, or congestion relief markets within this study. Future work should extend the model to incorporate these pathways, which may significantly improve the business case of ESS by stacking multiple value streams. Such an extension would align modelling more closely with real-world operational strategies and policy incentives.

5. Technology development & generalisability

Finally, further research should continue to track the techno-economic development of LDES technologies such as iron-air batteries, whose assumed performance is still based on early-stage projections. At the same time, the modular design of the model enables straightforward adaptation to other demand contexts and sectors. The findings of this research are closely tied to the continuous electricity demand of the chemical sector, where flexibility is limited and ESS must bridge extended REG shortages. As described in section 7.3.3, sectors with more flexible load profiles, enable better alignment with intermittent REG supply. In such cases, SDES or hybrid ESS solutions may prove more effective and economically attractive. A promising future research direction includes testing how reduced SDES costs, when combined with these more flexible demand patterns, could unlock the potential of hybrid ESS solutions in sectors beyond the chemical industry. This underlines both the sector-specific insights of the present study and the generalisability of the modelling approach as a tool for designing LES strategies under diverse conditions.

6. Include Broader System & Grid Effects

This study analysed a single-site application, modelled as one node (see section 3.2.3). Future research should extend this scope to multi-site or cluster-level configurations, such as energy hubs or partially grid-connected systems. The performed expert interviews as described in section 6 highlighted possible regional benefits with grid expansion and the inclusion of the surrounding grid would allow assessment of system-wide effects including shared infrastructure, joint investments, regional balancing, and deferred TSO reinforcements. Incorporating these broader system effects would provide a more holistic picture of the role of LES within the wider energy system and help policymakers identify when decentralised solutions can complement rather than substitute grid expansion.

By pursuing these directions, future research can enhance the relevance and applicability of LES modelling. The framework developed in this study is intentionally modular and flexible, allowing it to be readily adapted to other industrial use cases, sectors, or national contexts. This ensures its continued value in supporting decarbonization pathways under a range of future scenarios.

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Appendix A | Key publications

Author and year	**Objective**	**Model approach**	**Type of system**	**Conclusion**
(Prenzel et al., 2025)	Decarbonization concept of a chemical site utility system	TOPENERGY – energy system optimization annuity	Renewable Power Purchase Agreement (PPA) + green H_2 + TES	Molten salt TES can achieve 27% costs saving
(Wang et al., 2020)	Sector coupling with wind power and battery storage	gPROMS® Dynamic optimization approach	Ammonia-Nitric acid with Wind and BESS	Wind + BESS increases ROI with 5%
(Madeddu et al., 2020)	Potential of direct electrification technologies in chemical industry	bottom-up analysis of energy demand to identify the achievable level of electrification and its climate change mitigation potential	Direct electrification – e-boilers, MVR, induction, e-furnaces, plasma, heat pumps	78% is electrifiable with mature tech. 99% is electrifiable with immature tech.
(C. Chen & Yang, 2021)	Process flexibility with optimized energy storage	GAMS with CPLEX solver to minimize the levelized cost	Methanol	
(Du et al., 2025)	Steady state decarbonized chemical production	Aspen Plus and Chemkin to assess ESS requirements for RES chemical plants with no grid connection and no RES curtailment.	Green ammonia production with Lithium (SDES) and H_2 (LDES)	Diverse energy system is optimal for long term energy strategy
(López-Ceballos et al., 2025)	profitability assessment of integrating PHPS (LDES) with heat pumps and Li-ion batteries (SDES).	PVSyst® and EnergyPlus® + Matlab optimization for main components.	Electrified building with PV Power to Heat to Power (PHPS) with Heat pump	Systems combining peak power (SDES) and baseload storage (LDES) are most efficient
(Bogomolov & Ein-Eli, 2025)	Challenging li-ion batteries with MABs and RFB	Market and system analysis	Metal Air batteries	Iron-air needs further research to become feasible and mature
(Denholm et al., 2023)	Explain challenges and Opportunities for Long(er)-Duration Energy Storage.	-	Lithium	Li-ion dominates storage, but longer-duration technologies gain interest
(Farivar et al., 2023)	Explanation of Grid-Connected Energy Storage Systems and emerging technologies		5 categories of ESS: Electrical Mechanical, , Electrochemical, Chemical, and Thermal	

(Dechany et al., 2023)	Assessment of process implications to electrify ammonia (NH_3) production	Multiple scenario approach to electrify existing process	Haber Bosch + Steam Methane + Reformer and HB + Electrolyser + H_2	Electrolysers can reduce CO_2 up to 99%
(Nayak-Luke et al., 2018)	Identify the key variables that impact the levelized costs of ammonia LCOA	MATLAB quantitatively optimization model	Green ammonia + Renewable Energy + H_2	1 LCOE, 2 CAPEX electrolyser, 3 RE source ratio, ASU, HB power 4 and ramping rate5
(Prenzel et al., 2023)	Optimal integration of Molten Salt TES on chemical sites	Top-Energy® - Operational optimization model		Molten salt TES can reduce system costs by up to 27%
(Klasing et al., 2018)	Retrofitting combined heat plants to Renewable energy		Power to Heat with molten salt thermal energy storage	Understanding of possible flexibility measures for supply of chemical industry
(Alva et al., 2018)	Overview of thermal energy storage technologies		3 categories Sensible, Latent, Chemical.	Different technologies with

Appendix B | TRL Levels

TRL is a standardized methodology developed by NASA and later adapted by the EU to compare applications for the Horizon 2020 program. Nine categories are being distinguished to indicate the maturity of a technology:

TRL 1 | Basic principles observed

TRL 2 | Technology concept formulated

TRL 3 | Experimental proof of concept

TRL 4 | Technology validated in lab

TRL 5 | Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6 | Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 7 | System prototype demonstration in operational environment

TRL 8 | System complete and qualified

TRL 9 | Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Source: European Commission.

Appendix C | Annuity factor & Model constraints

The model annualises investment costs using a formula that calculates the annuity factor, which is used to annualise investment costs over the technical lifetime of an asset, accounting for a fixed discount rate. Mathematically, it is defined as:

$$a = \frac{r}{1 - (1 - r)^{-n}}$$

In which:

- r is the discount rate (expressed as a decimal, e.g., 0.07 for 7%)
- n is the economic or technical lifetime (in years)

This factor is then used to convert one-time capital investments (CAPEX) into a constant annual payment over the asset's lifetime. It ensures that future payments are discounted properly, so that the total value over time equals the initial investment. Within the model this formula is used to compute the annualised capital cost in €/MW/year or €/MWh/year, by multiplying the investment cost with this annuity factor and adding fixed O&M costs (FOM).

$$Annualised\ capital\ cost = Investment \times \left(\frac{r}{1 - (1 - r)^{-n}}\right) + FOM$$

In which:

- r is the discount rate (expressed as a decimal, e.g., 0.07 for 7%)
- n is the economic or technical lifetime (in years)
- FOM represent the Fixed Operation and Maintenance costs

Model Constraints:

Power balance | The energy balance equation is the most important constraint. Because it guarantees that the energy flow balances demand and supply at each bus (n) for each time (t).

$$\sum_{g \in G} P_{g,t} + \sum_{s \in S} \left(P_{s,t}^{ch} - P_{s,t}^{dis}\right) - \sum_{l \in L} P_{l,t} = D_t$$

- $P_{g,t}$ is the power generated by generators at time t (positive contribution to supply).
- $P_{s,t}^{ch}$ is the power charged into ESS at time t (draws power from the system → negative contribution).
- $P_{s,t}^{dis}$ is the power discharged from storage at time t (adds power to the system → positive contribution).
- $P_{l,t}$ is the net transmission power flow at time t (typically, exports are negative, and imports are positive).
- D_t: Electricity demand at time t.

The sum of generated power and net discharge from storage, minus the net transmitted power, must equal the demand at each time step. This guarantees that electricity supply and demand remain balanced across the system.

Generation constraints | Generators must operate within their nominal capacity limits, which are determined by resource availability. In this model, generators represent solar and wind technologies, with capacity factors derived from open-source weather data. Their dispatch is constrained by the following inequality:

$$0 \leq P_{g,t} \leq P_g^{max}$$

- $P_{g,t}$ is the power generated by generators at time t (positive contribution to supply).
- P_g^{max} is the maximal nominal power capacity of the installed generators

Energy storage constraints | The state of charge (SoC) of each ESS evolves over time based on charging and discharging activities. This dynamic is explained by the following equation:

$$E_{s,t} = E_{s,t-1} + \eta_s^{ch} \times P_{s,t}^{ch} - \frac{P_{s,t}^{dis}}{\eta_s^{dis}}$$

Charging and discharging efficiencies η_s^{ch} and η_s^{dis} are included to reflect energy losses in the ESS. The SoC must remain within the optimized capacity limits of the ESS:

$$0 \leq E_{s,t} \leq E_s^{max}$$

In this model, storage energy capacity E_s^{max} is linked to the installed power capacity P_s^{max} by a fixed discharge duration h_s^{max}.

$$E_s^{max} = P_s^{max} \times h_s^{max}$$

Grid expansion constraints | within the model a power capacity is assumed to be installed as existing grid connection for the chemical plant.

$$|P_{l,t}| \leq P_l^{max}$$

Grid connections can be expanded up to given limits $\bar{P}_l$ with the following equation:

$$0 \leq P_l^{max} \leq \bar{P}_l$$

Appendix D | Interview protocol

01 interview industry experts

Thesis | How to thrive without the grid?

Project:	Thesis | MoT	Date:	10-6-2025
Location:	Online	Time:	13:00 – 14:00
Chair:	S. Renders	Copy:	N.A.
Note taker:	S. Renders		
Present:	Name: 1. Stan Renders 2. Anonymous industry expert 1 3. Anonymous industry expert 2		
Absent:	1. …		

Protocol:

Check for informed consent.

1. Modelling Results

Objective: Inform industry experts about the modelling results and gather their perspectives on the findings.

1. Research approach
2. Model formalization & input parameters
3. Scenario analysis
4. Sensitivity analysis

Questions:

A. How do you interpret the modelling results? Do they align with your expectations?
B. To what extent do the modelled configurations reflect realistic solutions for chemical processes?
C. Which factors do you consider most critical for the chemical industry when investing in energy storage systems? (For example: CAPEX, OPEX, technology readiness level (TRL), maintenance)
D. Which other aspects do you think are important for the adoption of a local energy system but were not included in this research?
E. How could you use the results of my thesis in your work?

2. Decarbonizing the Chemical Industry

Objective: Gain a broader understanding of the decarbonization potential of the chemical industry to position this research within the larger decarbonization challenge.

Questions:

A. Which chemical processes do you consider technically and economically suitable for decarbonization? Which technologies do you think will play a role in this?
B. In your view, what are the main technological or operational barriers to the electrification of these processes?
C. Do you believe that local energy systems with storage can provide a long-term competitive advantage for the Dutch chemical industry?
   i. **If YES:** Which technologies do you consider the most promising?
   ii. **If NO:** What kind of support would you require from the government, grid operators, or other stakeholders to make this transition feasible?
D. Are there already specific ideas or plans within the sector that come to mind in this context?

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3. Market Dynamics

Objective: Reflect on current market developments and identify potential research recommendations.

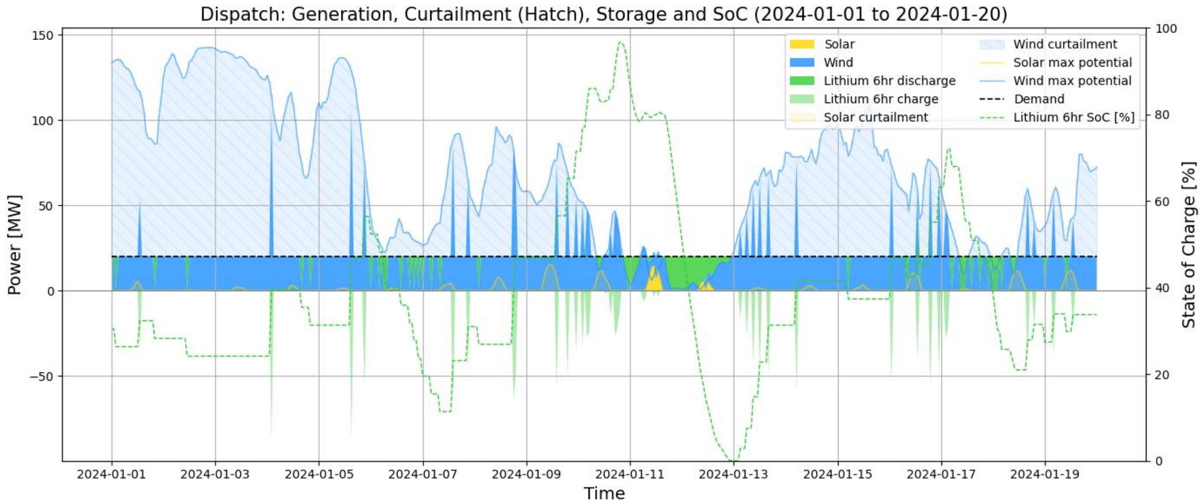
Questions:

A. How do you assess the current policy and regulatory environment regarding industrial decarbonization?
B. To what extent do energy prices, CO_2 levies, or flexibility contracts (such as ATR85/15) influence your decision-making on energy systems?
C. Do you see opportunities for new business models around energy storage, such as energy arbitrage, grid services, or flexibility markets?
   i. **If YES**: How do you evaluate the distinct characteristics of SDES and LDES for application in the chemical sector?
   ii. **If NO:** What limitations do you see in implementing energy storage systems at industrial sites?
D. Do you consider the current pace of market and policy developments sufficient to maintain industrial activities within the Dutch chemical sector?
   iii. **If YES**: Which developments do you consider most effective in supporting industrial electrification?
   iv. **If NO**: What conditions would need to change for you to have confidence in the long-term sustainability of the chemical industry in the Netherlands?

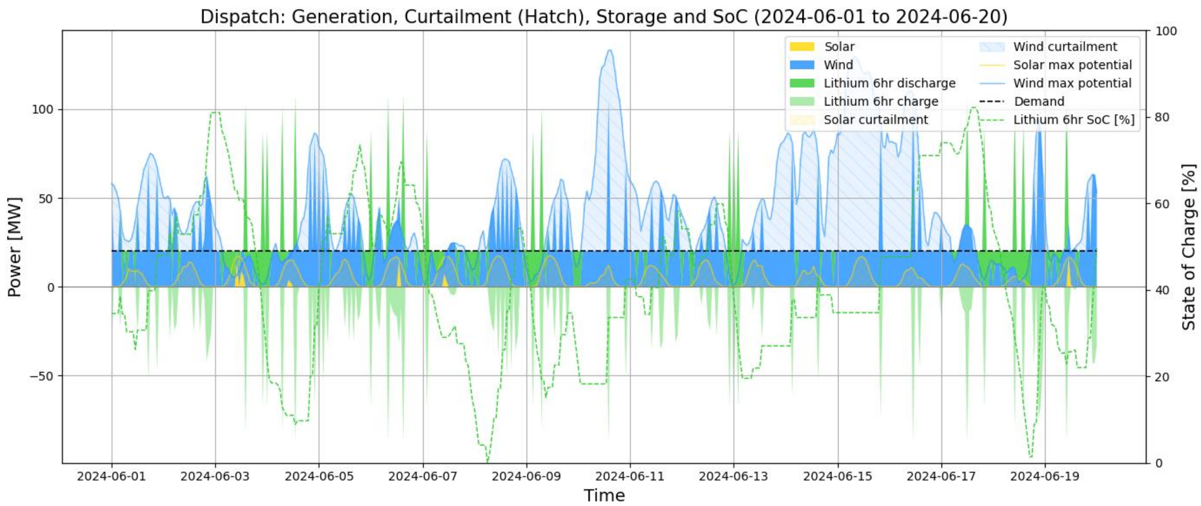
Closing:
Do you have any final comments or recommendations you would like to share regarding this interview or the modelling approach used in the research?

Appendix E | Dispatch plots January & June

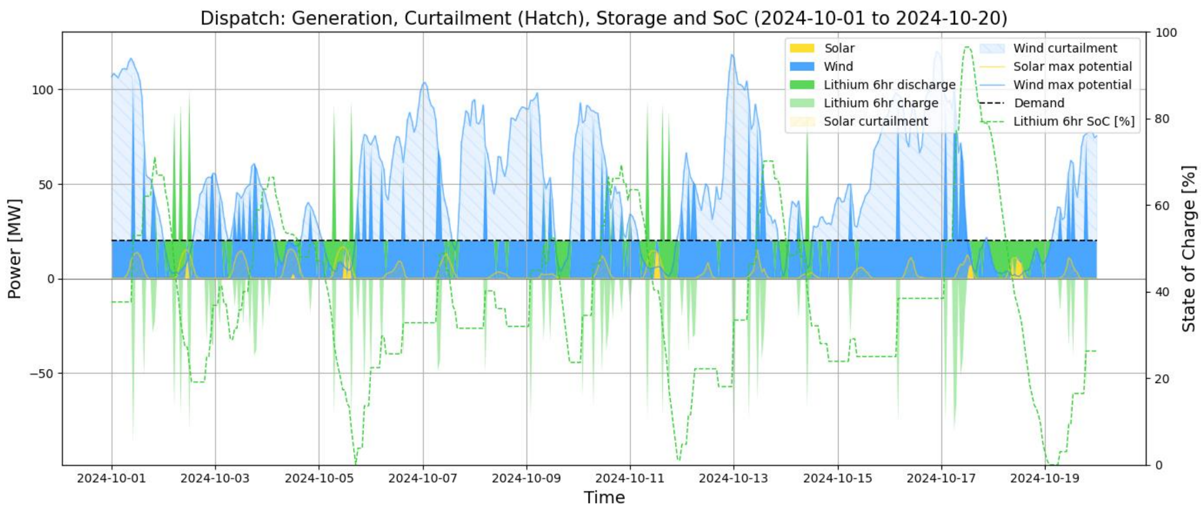
Scenario A | Winter



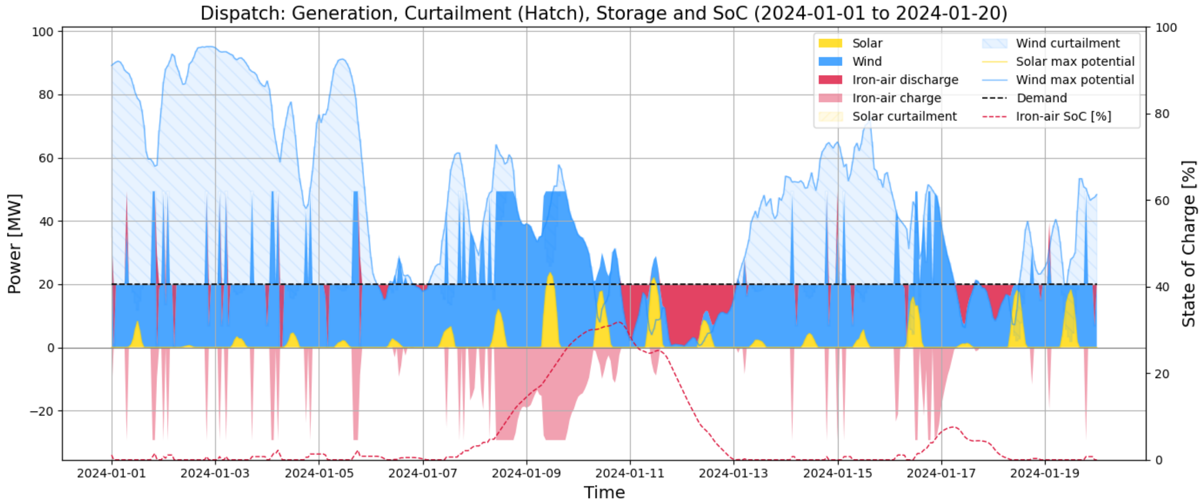
Summer



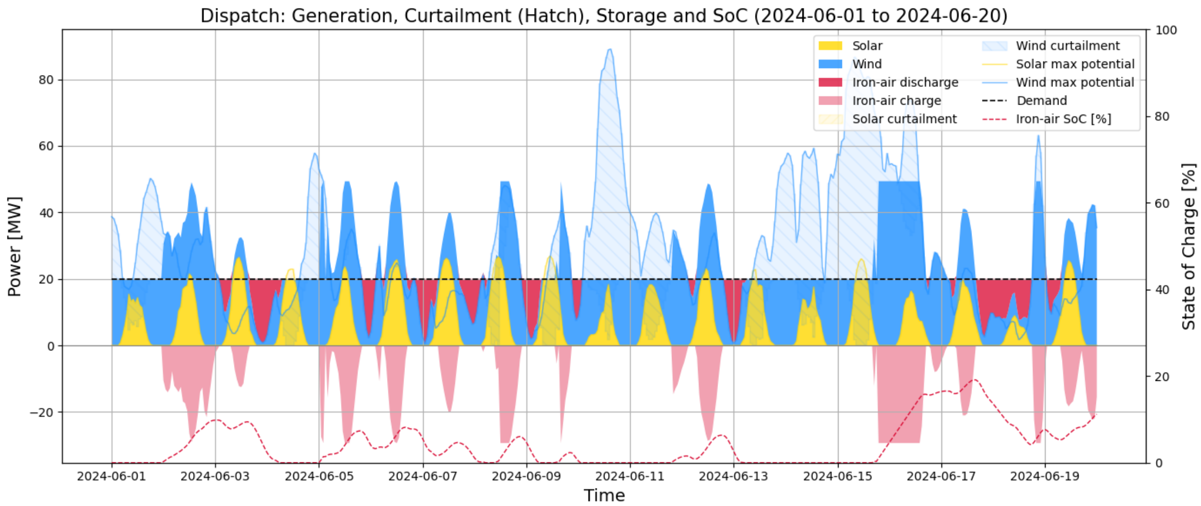
Autumn



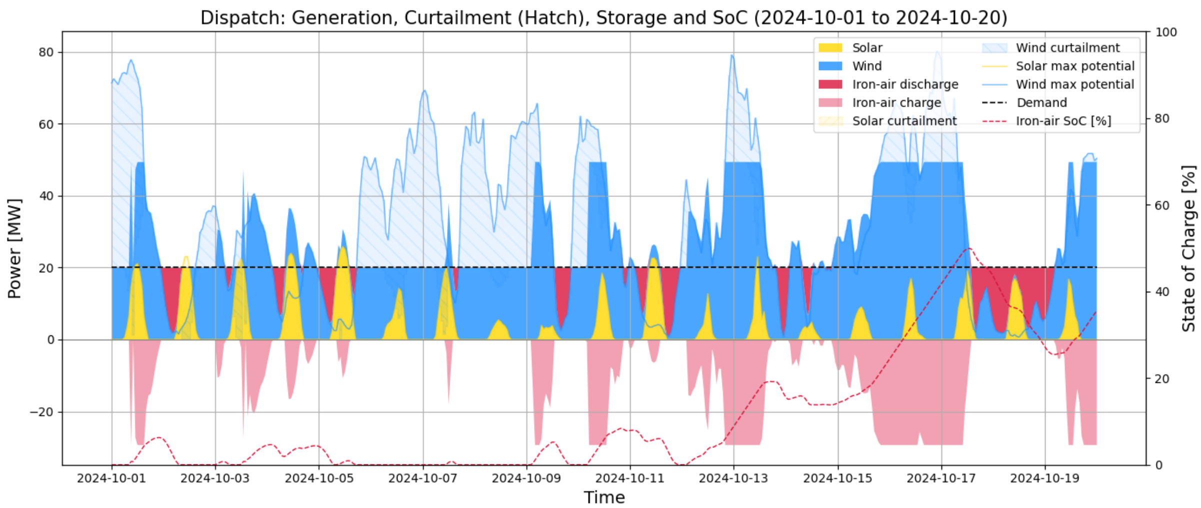
Scenario B | Winter



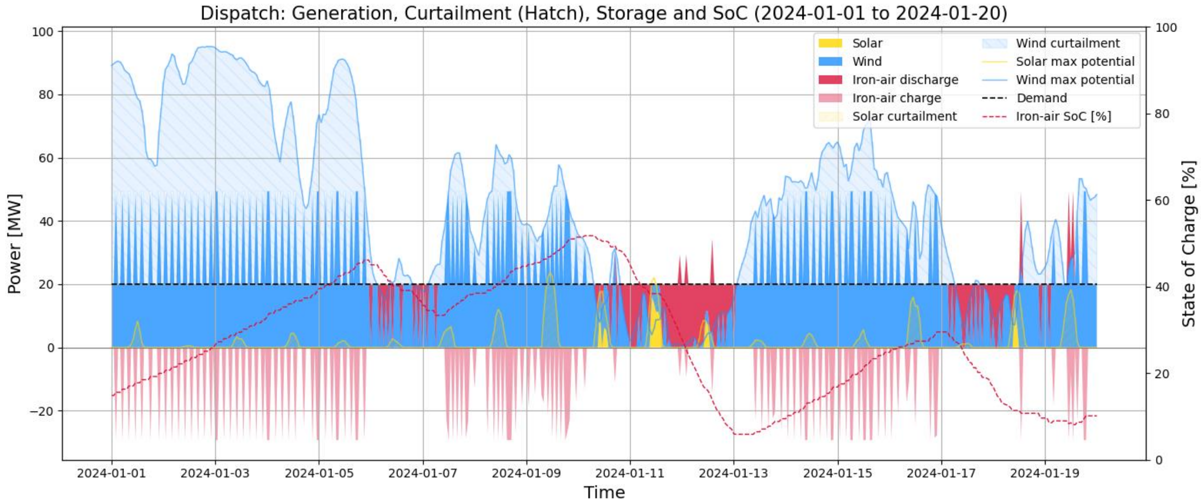
Summer



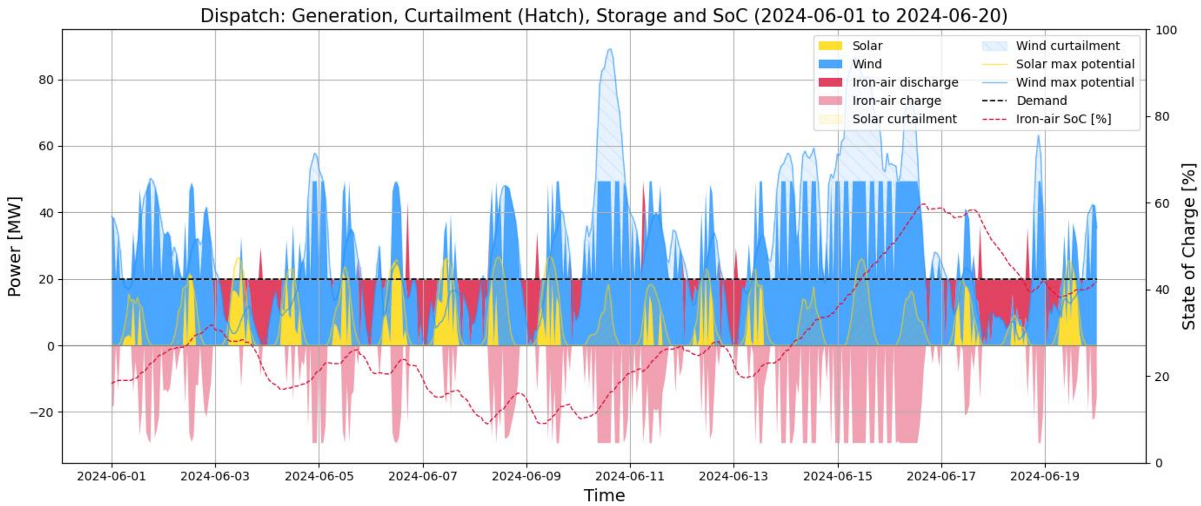
Autumn



Scenario C | Winter



Summer



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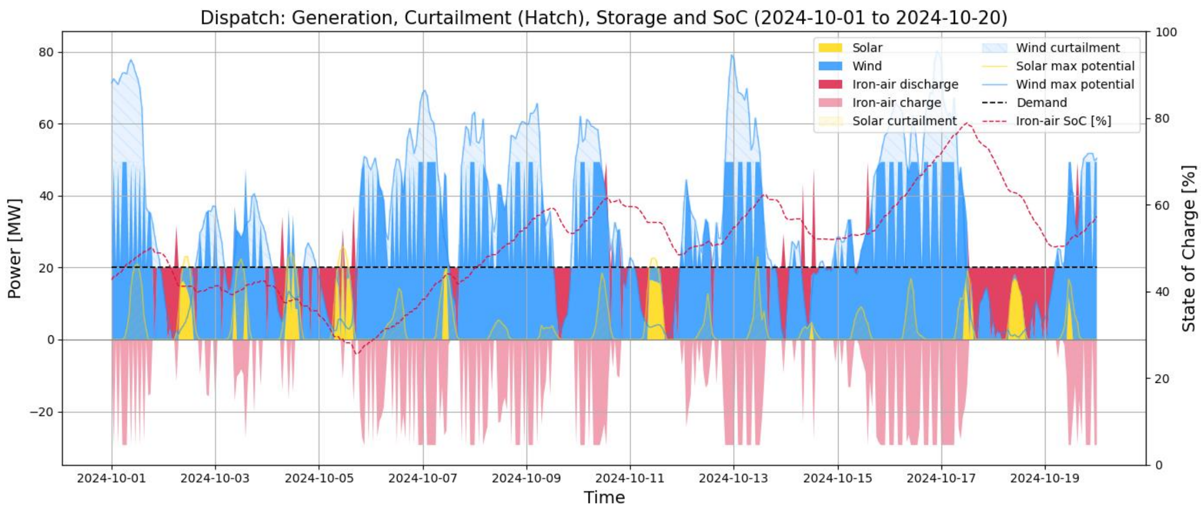
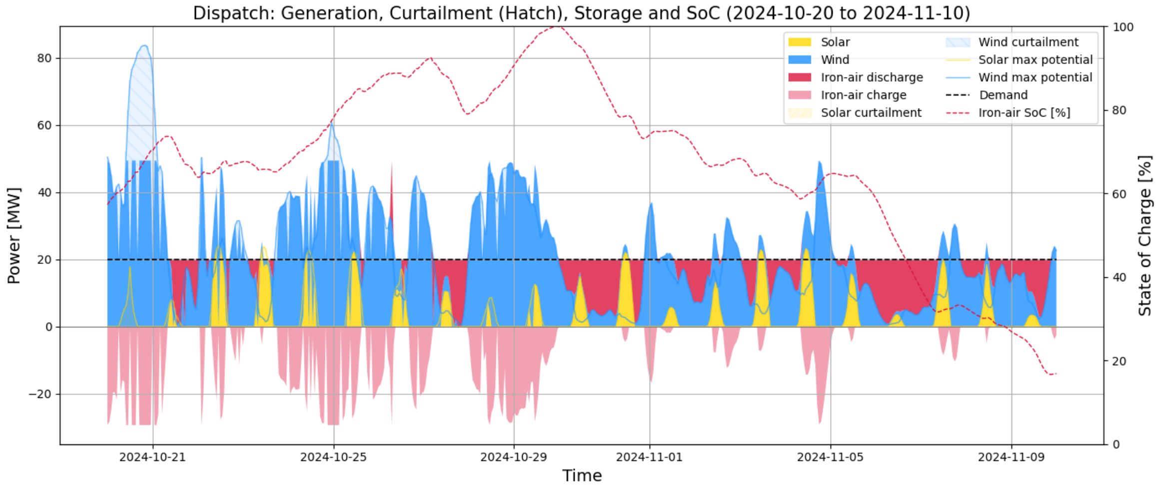


Appendix F | Dispatch plots fluctuating demand

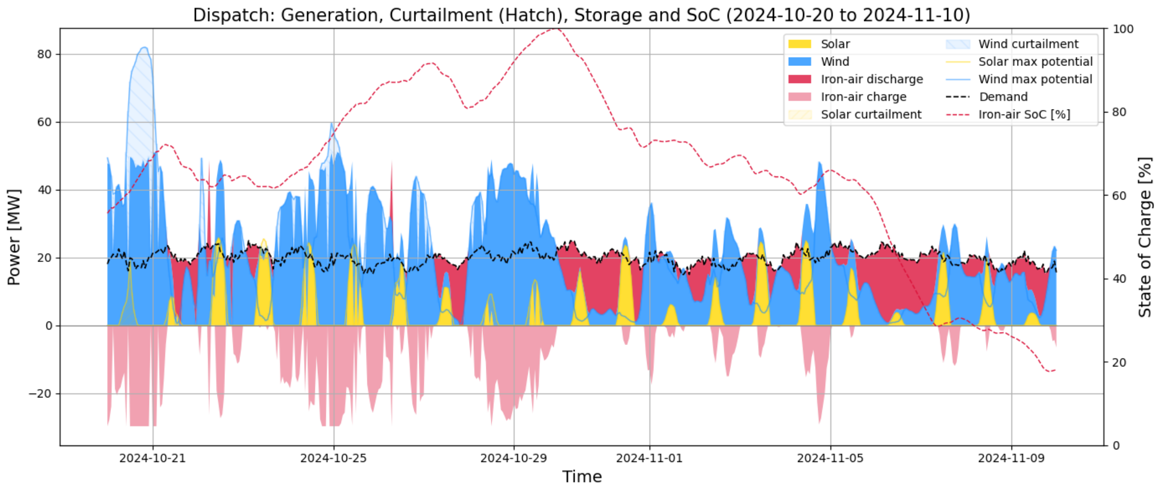
Scenario C | flat demand

Capacity rates: wind = 23.36%   solar = 4.88%



Moderate demand fluctuations

Capacity rates: wind = 23.48%   solar = 5.08%



Intense demand fluctuations

Capacity rates: wind = 24.77%   solar = 5.43%