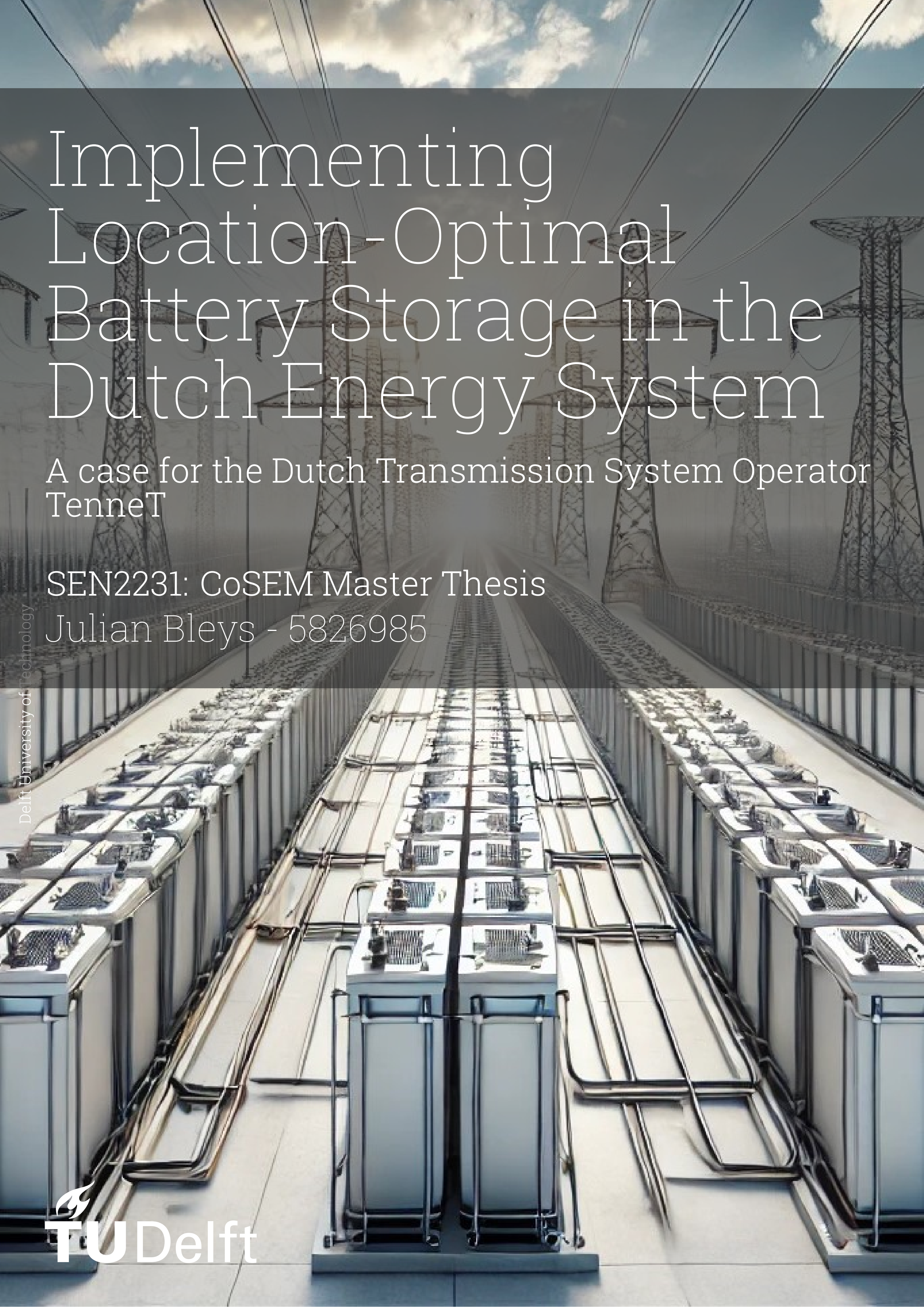

Implementing Location-Optimal Battery Storage in the Dutch Energy System

A case for the Dutch Transmission System Operator TenneT

SEN2231: CoSEM Master Thesis

Julian Bleys - 5826985

Delft University of Technology

TU Delft

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by

Julian Bleys - 5826985

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First supervisor:	Dr. K. Bruninx
Second supervisor:	Dr. G. Bekebrede
Chair:	Dr. G. Bekebrede
TenneT supervisor:	Emmanuel van Ruitenbeek
Project Duration:	September, 2024 - March, 2025
Faculty:	Faculty of Technology, Policy, and Management, Delft

TU Delft

Preface

This thesis marks the end of my academic journey. I want to express my gratitude to everyone and everything that made this journey possible since I have learned a lot from all the projects, exams, and people I encountered during this time. I made many friends, developed new hobbies and skills, and discovered the things I am passionate about. I can say with full confidence that I am ready for the challenges that lie ahead, and look forward to taking those on.

If one thing, this thesis taught me that taking on challenges is a part of my personality and that it is driving me to get the most out of everything I do. This thesis phase has challenged me more than I could have imagined both on a professional and personal level. I have had to reach out for help across many different companies and universities as my modeling experience was limited. Furthermore, I have rewritten my ideas and findings many times over. The persistence to carry on in spite of the many setbacks, was given to me by the wonderful people around me and for that, I want to thank those people for believing in me and carrying me through this project.

First of all my TU Delft supervision: Kenneth for thinking of new creative approaches when I was stuck. Despite the immense amount of students you had under your wing, you still managed to give me new insights every week. Geertje, thank you for offering the outside-perspective on my work I sometimes needed.

As for TenneT, thank you Joost, Timm, and Emiel for offering me the learning environment in which I was able to grow. Emmanuel, it goes without saying that you helped me through this project by a lot. I will miss the Monday morning catch-up sessions that were always filled with humor and great insights. I sincerely hope we get to work together somewhere in the future, but it does seem that way.

Furthermore, I would like to thank my family and friends for the environment of trust and reassurance I needed to embark on- and finish this project. Mieke, thank you for supporting my ambitions. Bart, thank you for always making me laugh. Anne, I look up to you and I know you will always be there for me. Alys, you are an incredible woman and if it weren't for you, I would not have been able to do this. Your persistent positive attitude and love have carried me through the times when I needed it the most. Finally, TU Delft friends like Tom, Jacob, and Timo always managed to put things in perspective and made my study time in Delft that much more fun and valuable.

One of the greatest learnings from this study program can be captured by the quote: "Navigating complex systems is not about having all the answers to reach a final state, but about knowing which questions to ask to move to the next step."

Having extended my gratitude, I sincerely hope that you enjoy reading my thesis report.

Julian Bleys - 5826985
Delft, February 2025

Summary

The Dutch electricity system is undergoing a rapid transformation due to the increasing penetration of variable renewable energy sources (vRES) and the growing need for grid flexibility solutions. Battery Energy Storage Systems (BESS) are widely recognized as a key enabler of this transition, offering services such as grid congestion management, renewable integration, and frequency regulation. However, there is currently no systematic strategy for the optimal placement of large-scale BESS in the Dutch high-voltage (HV) grid. This lack of clarity leads to inefficiencies in grid planning, increased system costs, and uncertainty for market participants. Market parties seek to secure grid connections as soon as possible to stay ahead of market cannibalization, while Transmission System Operator (TSO), TenneT, lacks sufficient insights into the long-term system implications, leading to suboptimal grid planning and investment decisions. Additionally, limited land availability and competing spatial claims further complicate the feasibility of large-scale storage deployment, raising the question of how spatial constraints and economic land-use considerations impact BESS allocation, system costs, and grid performance.

To address this issue, the study is guided by the following main research question:

"What is the impact of spatial constraints and economic land-use considerations on the optimal placement of large-scale battery energy storage systems (BESS) from the perspective of the TSO in the Dutch High-Voltage grid?"

This question is further divided into three sub-questions, each addressing a key component of BESS placement and system integration:

SQ1. *What are the relevant considerations in the process of BESS development and placement according to academic literature and real-world experts in the Netherlands?*

SQ2. *What is the impact of imposing restrictions related to competing land use and exclusion areas on the optimal placement of BESS?*

SQ3. *What is the impact of including the cost of land in the consideration of BESS placement in the model?*

Each of these research questions is addressed through a mixed-methods approach combining a literature review, expert interviews, and an optimization model (implemented in PyPSA-Eur) to evaluate different BESS placement scenarios across two temporal snapshots (2023 and 2040) from the perspective of TSO TenneT. The first research question is tackled in Chapter 2, where a comprehensive literature review and interviews with experts from TenneT and market participants provide insights into BESS siting challenges, permitting barriers, and spatial planning limitations. These findings shape the spatial and economic constraints used in the optimization model.

The second and third research questions are addressed through optimization modeling in Chapters 3, 4, and 5. The model evaluates BESS placement under three distinct scenarios: a BASE scenario without major land-use restrictions, a COL scenario incorporating regional land costs, and an EXCL scenario applying strict spatial exclusion zones. The model optimizes BESS placement based on system cost minimization, balancing grid congestion relief, land availability, and economic feasibility.

The case study applied the model to the Dutch HV grid, clustered into 37 nodes to balance computational efficiency and spatial resolution. The 2023 scenario represented current grid conditions, while the 2040 scenario modeled a high-electrification future with ambitious decarbonization targets. The results highlight the crucial role of BESS in maintaining grid stability and system cost efficiency. In 2023, strict exclusion zones led to a 43% reduction in BESS capacity, while land costs had a minor impact. By 2040, the dependence on BESS significantly increased, with the EXCL scenario still reducing capacity by 19%. Interestingly, in 2040, certain nodes that previously received little or no BESS capacity in the

EXCL scenario saw a dramatic increase in BESS allocation, indicating an inherent system need for storage despite suboptimal placement constraints.

Beyond BESS allocation, the results revealed several additional system dynamics between 2023 and 2040:

- **Expansions of cross-country HVDC connections**, particularly between the Netherlands and Great Britain in scenarios where BESS was spatially constrained.
- **Stable average line loading and peak frequency**, indicating that despite spatial constraints, the grid adapted by relying more on transmission expansion and flexible generation.
- **BESS allocation near renewable energy (RE) generation hotspots**, which often coincided with high-demand locations and industrial clusters, reinforcing the role of co-located storage for balancing local grid fluctuations.

The discussion section contextualizes these findings, emphasizing that while market-driven BESS deployment does not immediately worsen congestion, strategic placement is essential as renewable penetration increases. Even under spatial constraints, the grid adapts through alternative flexibility measures, such as increased reliance on cross-border HVDC transmission. However, the long-term implications of this adaptation remain uncertain. A structured BESS deployment strategy would provide clarity for multiple stakeholders: BESS developers would gain insights into viable locations and revenue streams, TenneT could align storage deployment with system needs, and policymakers could anticipate land-use requirements.

Policy recommendations include a national BESS deployment roadmap, streamlined permitting, and differentiated grid connection fees to prioritize BESS placement where it delivers the highest system benefits. Despite its contributions, this study has some limitations. The use of the solar-PV availability matrix as a proxy for BESS siting limits spatial resolution at the station level, meaning real-world land constraints near substations are not fully captured. Additionally, other flexibility options such as demand-side response and alternative storage technologies were not considered, which may provide complementary or competing solutions. Furthermore, stakeholder misalignment between TSOs, market participants, and regional governments remains a key barrier to system-optimal BESS deployment.

In conclusion, while spatial constraints significantly impact BESS placement, grid resilience remains intact across scenarios. Economic land costs play a minor role compared to zoning and technical constraints, emphasizing the need for stronger integration between spatial planning, regulatory policies, and energy system modeling. This study contributes to bridging the gap between energy infrastructure planning and land-use policy, supporting a cost-effective, spatially efficient, and strategically integrated BESS deployment strategy. Future research should refine long-term storage planning by incorporating detailed station-level spatial modeling, broader flexibility solutions, and dynamic policy and market mechanisms.

The code that was used to answer the research questions can be accessed at:

https://github.com/JuulRB/PyPSA-Eur-for-Optimal-BESS-allocation/tree/master

Keywords: *Battery Energy Storage Systems, renewable energy, spatial optimization, energy system modeling, Dutch electricity grid, socio-technical systems.*

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Nomenclature

Abbreviations

Table 1: Abbreviation table

Abbreviation	Definition
AC	Alternating Current
ATR	Alternative Transport Right
BESS	Battery Energy Storage System
CLC	Corine Land Cover
COL	Cost-of-Land
DAM	Day-Ahead Market
DC	Direct Current
DSO	Distribution System Operator
EIA	Environmental Impact Assessment
EoL	End-of-Life
ESS	Energy Storage System
EXCL	Exclusion Scenario
GRIM	Greenfield Renewables Investment Model
HV	High-Voltage
HVDC	High-Voltage Direct Current
KWh	Kilowatt Hour
Li	Lithium
MW	Megawatt
PEH	Programma Energiehoofdstructuur
PV	Photovoltaics
PyPSA	Python for Power System Analysis
RES	Renewable Energy Sources
SQ	Subquestion
STS	Socio-Technical System
TSO	Transmission System Operator
TWh	Terawatt Hour
vRES	Variable Renewable Energy Sources

Symbols

Symbol	Definition	Unit
C_{gen}	Cost of electricity generation, including fuel and variable O&M costs	[€/MWh]
$C_{\text{transmission}}$	Costs related to transmission line utilization and expansions	[€/MWh]
C_{storage}	Cost associated with energy storage, such as charging, discharging, and efficiency losses,	[€]
C_{density}	Capacity density of the BESS technology	[ha/MWh]
D_{t}	Electrical power demand	[MW]
P_{ch}	Storage charging power	[MW]
P_{dis}	Storage discharging power	[MW]

Symbol	Definition	Unit
P_{gen}	Electrical power generation from all sources	[MW]
P_{l}	Transmission line power	[MW]
P_{import}	Power imported from external grids	[MW]
P_{export}	Power exported to external grids	[MW]
E_{s}	Energy capacity of storage technology	[MWh]
R_{trans}	Transmission line resistance	[Ω]
F_{flow}	Power flow through transmission lines	[MW]
L_{land}	Land required for battery installation	[ha]
V_{node}	Voltage at a node in the high-voltage network	[kV]
T_{trans}	Transformer capacity	[MVA]
D_{dist}	Distance between nodes in the transmission grid	[km]
G_{gen}	Generation capacity at a specific node	[MW]
h_{s}	maximum discharge time	[s]
ρ_{energy}	Energy density of the battery	[MWh/m^3]
η_{g}	Generation efficiency of the battery	[%]
η_{ch}	Charging efficiency of the battery	[%]
η_{dis}	Discharging efficiency of the battery	[%]
ϵ_{g}	Emission factor	[0]
α_{loss}	Fraction of energy lost during transmission	[%]
β_{max}	Maximum allowable state of charge of the battery	[%]
γ_{min}	Minimum allowable state of charge of the battery	[%]
λ_{CO2}	CO_2 emission factor for grid electricity	[kg CO_2/MWh]
δ_{voltage}	Voltage deviation from nominal value	[%]
θ_{angle}	Phase angle difference between nodes	[rad]
ϕ_{penalty}	Penalty factor for unmet demand	[€/MWh]

1
Introduction

1.1. Problem Statement

The transition to a decarbonized energy system is a critical global challenge, with international agreements such as the Paris Agreement (UNFCCC, 2018) and the European Council's climate goals (European Counsil, 2023) reinforcing the urgency to achieve carbon neutrality by 2050. The energy sector is responsible for approximately 73% of global anthropogenic CO_2 emissions, making the decarbonization of electricity generation a priority (Intergovernmental Panel On Climate Change (Ipcc), 2023). However, increasing electricity demand and growing reliance on weather-dependent renewable generation have introduced new operational challenges, particularly regarding grid stability and flexibility (Zahraee et al., 2016). Managing these fluctuations requires integrating flexible generation, demand response, and grid expansion (Schmidt & Staffell, 2023). The Netherlands, with its ambition to integrate at least 35 TWh of renewable electricity generation on land, is particularly in need of effective flexibility solutions to accommodate the intermittency of wind and solar power (Ministerie voor Klimaat en Energie, 2023; van Gastel, 2024).

Among the available flexibility options, Battery Energy Storage Systems (BESS) have gained widespread attention due to their ability to store and release electricity when needed, helping to mitigate grid imbalances, congestion, and the variability of renewable energy sources (Cole et al., 2021; Wong, Ramachandaramurthy, Walker, et al., 2019). Lithium-ion (Li-ion) BESS are particularly favored for their high energy density, cycling stability, and declining costs (Figgener et al., 2020). TenneT estimates that between 5.2 and 12.7 GW of large-scale (>70 MW) BESS will need to be installed by 2030 to support system reliability (TenneT, 2024d). However, BESS grid connection applications have already surpassed 70 GW, illustrating that market parties want to stay ahead of market cannibalization (Schmidt & Staffell, 2023), and that a disconnect exists between system needs and market-driven deployment (Flevoland, 2024; Repowered & APPM, 2023).

For Transmission System Operators (TSOs) like TenneT, this lack of clarity on optimal BESS siting is problematic, as grid expansion plans and reinforcement investments rely on assumptions about the regional availability of flexibility. If actual BESS deployment deviates from these assumptions, there is a risk of inefficient infrastructure investments, higher system costs, and suboptimal congestion relief strategies. Additionally, uncertainty in BESS planning extends to policymakers and market parties, creating investment risks and delays in policy development. Without a strategy informed by robust system-level insights, BESS deployment could be misaligned with broader decarbonization goals, reducing its potential to enhance grid resilience.

The Netherlands' high population density and limited land availability further complicate the scalability of BESS, requiring careful planning to ensure that deployment aligns with spatial and regulatory frameworks (Selim et al., 2020). Installing 5.2–12.7 GW of BESS is projected to require 23–33 km² of land, making spatial considerations a critical factor in storage feasibility (Netbeheer Nederland, 2023). The recently introduced Programma Energiehoofdstructuur (PEH) stresses the urgent need to integrate spatial planning into energy system modeling, yet highlights the lack of knowledge on how BESS placement affects the electricity system and land-use trade-offs (RVO, 2024a).

This thesis responds to these challenges by developing a spatially explicit optimization model using the PyPSA-Eur framework to evaluate cost-optimal BESS configurations in the Dutch high-voltage (HV) electricity grid. The model incorporates technical constraints, spatial restrictions, and economic land-use considerations, providing quantitative insights into the trade-offs between BESS placement, total system costs, and infrastructure needs. Furthermore, it assesses how spatial constraints influence grid expansion planning, ensuring that system-wide impacts are considered. By simulating different deployment scenarios, this study aims to provide actionable insights that support TSOs, policymakers, and market participants in designing a structured, cost-effective, and spatially efficient BESS deployment strategy for the Dutch electricity system.

1.2. Literature Gap

By 2030, electricity storage is projected to become the second-largest technical flexibility solution after flexible generation (Schmidt & Staffell, 2023). Consequently, researchers have increasingly focused on this topic, leading to a growing body of literature on energy storage systems (ESS), including BESS. Recent studies highlight the ability of BESS to effectively manage grid congestion, which has further driven academic interest in this area (Hazra et al., 2015; Peesapati et al., 2024). However, much of the existing research focuses primarily on optimizing the placement and operation of ESS from a technical perspective, leaving significant gaps in connecting these models with real-world applications. Engineers involved in the techno-economic design of energy systems often neglect geographical and institutional factors, while economists focusing on institutions tend to have limited expertise in techno-economic modeling. This disconnect between optimization models and institutional contexts underscores the need for a more comprehensive systems perspective (N. Wang, 2022). Moreover, the complexity of integrating BESS across multiple domains—such as energy, urban, and spatial planning—has not been sufficiently addressed in current literature (Gulan et al., 2019; J. Wang et al., 2022; N. Wang et al., 2020).

Bridging Energy System Planning and Urban Planning

One of the most pressing gaps in the literature is the insufficient connection between energy system planning and urban planning, particularly in spatially constrained environments like the Netherlands. With limited available land, the spatial impact of large-scale BESS installations is significant, as spatial constraints must be carefully considered to align renewable energy infrastructure with land-use policies. For example, studies such as those by N. Wang et al. (2020) on variable renewable energy source (VRES) placement in the Dutch grid highlight the importance of efficient land use in estimating energy system potentials. They emphasize that well-designed spatial policies are critical for ensuring sustainable energy infrastructure development.

Despite this recognition, the specific impacts of spatial constraints—such as exclusion zones or competing land uses—on the optimal placement of BESS have not been sufficiently explored. The integration of spatial planning with energy system design remains underdeveloped in current research, leaving critical questions unanswered about how spatial constraints shape system costs and performance. This thesis contributes to addressing this gap by investigating the implications of land-use restrictions on the optimal placement of large-scale BESS in the Netherlands.

Multidimensional Socio-Technical Challenges

In addition to spatial considerations, the integration of BESS into energy systems involves a complex network of stakeholders, including TSOs, distribution system operators (DSOs), safety regulators, and manufacturers. These actors operate within overlapping regulatory, technical, and economic frameworks, creating uncertainties regarding how socio-technical transitions will unfold (Geels et al., 2018). Such uncertainty is compounded by the wide range of available technological alternatives, making it difficult to identify the most effective pathways for large-scale BESS deployment (Gür, 2018; Roberts et al., 2018).

This gap is further underscored by a limited understanding of the system-wide effects of BESS placement decisions. While the benefits of BESS in reducing system stress are well-documented, there is a lack of clarity on how placement decisions affect total system costs, grid congestion, and flexibility needs. Moreover, there is insufficient knowledge about whether certain placement configurations could inadvertently worsen system performance, highlighting the need to quantify the implications of what might be described as “misaligned” BESS placements (Castro & Espinoza-Trejo, 2023; Repowered & APPM, 2023).

Contribution of This Study

This thesis makes several contributions to the academic literature:

- **Bridging Energy System and Spatial Planning:** By exploring the implications of spatial constraints, such as land-use restrictions and exclusion zones, on BESS placement, this study connects the fields of energy system planning and urban planning. It highlights the importance of integrating spatial considerations into energy models to address real-world deployment challenges.
- **Understanding System-Wide Impacts:** The research provides insights into the broader system-level effects of BESS placement decisions, including the trade-offs between placement strategies and their impact on grid costs, congestion, and flexibility needs. This contributes to understanding how BESS placement influences the efficiency and resilience of the electricity grid.
- **Incorporating Socio-Technical and Economic Factors:** The optimization model developed in this thesis integrates not only technical constraints but also spatial and financial considerations, aligning with regulatory frameworks such as the Dutch PEH. By addressing these multidimensional factors, the research contributes to the growing body of knowledge on socio-technical transitions in energy systems.

These contributions aim to inform both academic research and practical policymaking, providing a foundation for strategic BESS deployment in spatially constrained environments like the Netherlands.

1.3. Research Questions

The deployment of large-scale BESS in the Dutch HV electricity grid requires careful consideration of spatial, economic, and technical factors. For TSOs, such as TenneT, understanding the system-wide effects of BESS placement is critical, as network expansion plans are based on assumptions about regional flexibility. Deviations from these assumptions can lead to inefficiencies in grid expansions, higher system costs, and uncertainty for market parties about future market opportunities.

This research develops a spatially explicit optimization model to evaluate the impact of spatial constraints and economic land-use considerations on BESS placement. The model optimizes total system costs, balancing capital expenditures for generation, storage, and transmission with operational and grid expansion costs.

In this context, ”optimal” refers to the cost-minimizing configuration that ensures grid stability while efficiently integrating BESS to reduce congestion, minimize renewable curtailment, and balance supply and demand. By incorporating technical, spatial, and economic constraints, the study provides insights for the cost-effective and spatially efficient deployment of BESS in the Netherlands.

The primary research question guiding this study is:

What is the impact of spatial constraints and economic land-use considerations on the optimal placement of large-scale battery energy storage systems (BESS) from the perspective of the TSO in the Dutch High-Voltage grid?

To address the main research question, the following sub-questions are considered:

SQ1. *What are relevant considerations in the process of BESS development and placement according to academic literature and real-world experts in the Netherlands?*

SQ2. *What is the impact of imposing restrictions related to competing land use and exclusion areas on the optimal placement of BESS?*

SQ3. *What is the impact of including the cost of land in the consideration of BESS placement in the model?*

Sub-question 1 focuses on understanding the key considerations influencing BESS placement. A literature review and expert interviews with TenneT and external market parties are conducted to identify regionally dependent factors, such as spatial constraints, proximity to infrastructure, and permitting challenges. These insights help define the systemic components and constraints to be included in the optimization model and guide the design of scenario analysis.

Sub-question 2 subsequently examines how spatial constraints, such as exclusion zones and competing land-use priorities, influence BESS placement decisions. By evaluating the availability of suitable locations under these constraints, the model provides insights into the trade-offs and challenges associated with aligning energy infrastructure with land-use policies. Additionally, this analysis highlights how alternative placement strategies impact system-wide costs and grid performance, providing actionable insights for TSOs to optimize grid investments.

Finally, sub-question 3 investigates the financial implications of BESS placement by incorporating land costs into the optimization model. This analysis explores how varying land prices affect the spatial distribution of BESS installations and the cost-efficiency of deployment strategies. The inclusion of land costs bridges the gap between technical optimization and practical financial considerations, ensuring that the findings are relevant to real-world decision-making.

This research aims to enhance understanding of the systemic factors influencing BESS placement and to adapt and extend the PyPSA-Eur framework to create a spatially explicit optimization model tailored to evaluate cost-optimal BESS configurations. The study contributes to bridging the gap between energy system planning and spatial planning by addressing the connection between financial and geographical constraints. By providing insights into the system-wide effects of BESS deployment, the research supports the development of a robust, spatially efficient strategy for integrating BESS into the Dutch electricity grid.

1.4. Scope

After having defined the research questions guiding this research, this section outlines the study's scope. This thesis investigates the optimal placement of large-scale BESS in the Dutch HV electricity grid, integrating spatial, technical, and regulatory constraints. The research focuses on the ultra-high voltage (UHV) 220 kV and 380 kV transmission network to address system-wide challenges such as grid congestion, flexibility needs, and the integration of vRES (TenneT, 2024a).

1.4.1. The High-Voltage Electricity Grid

The Dutch HV electricity grid, operated by TenneT, plays a crucial role in transmitting electricity from generation centers to demand hubs, ensuring system stability and efficiency (TenneT, 2024c). Electricity is transported at multiple voltage levels, including 110 kV, 150 kV, 220 kV, and 380 kV, with the latter two often referred to as UHV levels. However, in this research, the entire system operating at 110 kV and above is referred to as the HV grid.

Electricity is transported over long distances at the highest voltage levels (220 kV and 380 kV in the Netherlands) to minimize transmission losses (TenneT, 2024a). Transmission substations step down voltage levels to connect to the sub-transmission and distribution networks, which supply industrial, commercial, and residential consumers. This hierarchical structure ensures an efficient flow of electricity across the grid while reducing congestion and maintaining grid stability.

This study focuses exclusively on the 220 kV and 380 kV transmission network, excluding the 110 kV and 150 kV sub-transmission levels. By prioritizing the highest-voltage segments, the research directly addresses large-scale system challenges such as congestion management, renewable energy integration, and grid flexibility needs. This focus aligns with the strategic objectives of TenneT, including optimizing grid expansions, minimizing bottlenecks, and preparing for increased electrification.

1.4.2. Electricity Storage

The transition toward a renewable-dominated electricity system increases the need for flexibility solutions to manage vRES intermittency and grid congestion (IRENA, 2018). Flexibility refers to the extent to which a power system can adjust electricity demand or generation in response to both expected and unexpected changes (Taibi et al., 2018). It reflects the system's ability to maintain reliable supply during periods of transient or significant imbalances (Babatunde et al., 2020). According to a techno-economic definition by the IRENA (2018)(p.15): "Power system flexibility is the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of demand and supply across all relevant timescales”. Traditional flexibility relied on dispatchable generation, such as gas turbines, but the transition to RES has shifted this dynamic. Modern flexibility mechanisms are now critical for mitigating imbalances, supporting grid stability, and enabling renewable energy integration Among available options, BESS has emerged as a scalable and cost-effective technology, capable of providing multiple services such as frequency regulation, peak shaving, and energy arbitrage (Schmidt & Staffell, 2023).

Among available storage technologies, this study focuses on lithium-ion (Li-ion) BESS due to their high energy density, rapid response capabilities, and declining costs (Kintner-Meyer et al., 2010; Schmidt & Staffell, 2023). In line with large-scale storage developments, this research considers BESS installations exceeding 70 MW, as they directly influence HV grid flexibility and congestion management (Netbeheer Nederland, 2023).

BESS enhances economic viability through multiple revenue streams, including market-based revenues, ancillary services, and capacity payments. Value stacking further optimizes profitability by combining these streams—e.g., engaging in energy arbitrage during off-peak hours, providing frequency regulation during high-demand periods, and supporting voltage stability when needed (Schmidt & Staffell, 2023).

A key element in value stacking is connection and transport agreements, such as the Alternative Transport Right 85% (ATR85) in the Netherlands. ATR85, first applied in 2025 between TenneT and GIGA Storage, offers grid users access to transport capacity for 85% of the year at a reduced rate, with up to 15% curtailment notified a day in advance (Energy Storage NL, 2024; TenneT, 2024b). Without such agreements, BESS could lead to grid congestion rather than mitigate it (TenneT, 2024b).

The ATR85 contract provides several benefits:

- **Structured Agreements**: Ensures predictable income streams, improving financial planning for BESS operators.
- **Flexibility**: Allows operators to optimize revenue while adhering to grid constraints.
- **Investment Support**: Reduces operational costs and investment risks, enhancing financial feasibility.

1.4.3. System Network and Geographical Scope

In the Dutch energy system, TenneT, the TSO, plays a key role in managing and balancing electricity supply and demand. As the backbone of the energy infrastructure, TenneT also leads efforts to integrate renewable energy sources and deploy large-scale flexibility solutions, such as BESS, to meet national and European climate goals (TenneT, 2024c). Supporting this ecosystem are DSOs, responsible for regional distribution networks, and Gasunie, which integrates hydrogen and natural gas infrastructure into the broader energy transition framework.

Figure 1.1 highlights the research focus area (red box) within the broader Dutch electricity grid, emphasizing the importance of the HV network in addressing system-wide challenges like spatial restrictions and optimal flexibility placement.

The Dutch electricity system operates within a broader European energy market, with significant cross-border electricity exchanges influencing national grid stability (TenneT, 2024c). To capture these interactions, this study models the Netherlands while incorporating key neighboring countries—Belgium, Denmark, Germany, Great Britain, Ireland, and Norway. These regions are included to account for international power flows, interconnectivity constraints, and the role of cross-border flexibility mechanisms.

For spatial granularity, the study adopts the NUTS-3 classification, as defined by Eurostat (Eurostat, 2024). This classification was chosen over RES regions (Regionale Energiestrategie, 2022), due to its:

- **Higher spatial resolution** – Enabling refined analysis of optimal BESS siting.
- **Statistical compatibility** – Providing detailed energy, land-use, and economic data.
- **European comparability** – Aligning with broader EU-wide energy planning frameworks.

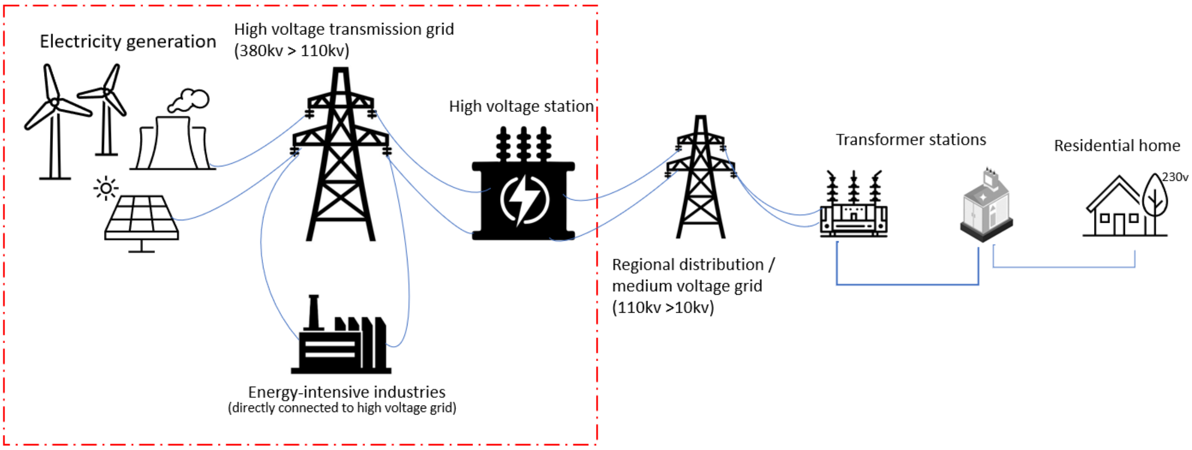


Figure 1.1: Simplified overview of the Dutch electricity grid and the research focus area (red box)

To balance accuracy and computational efficiency, the Dutch grid is clustered into 18 nodes, while the broader European grid is modeled using an additional 19 nodes. This approach ensures that the model captures detailed spatial dynamics within the Netherlands while maintaining computational feasibility (Frysztacki & Brown, 2020).

1.5. Research Approach

This section outlines the research approach adopted for this study, aimed at exploring the optimal placement of BESS within the Dutch electricity grid. The chosen approach integrates both qualitative interviews and quantitative modeling techniques, allowing the exploration of both qualitative insights and quantitative predictions, providing a holistic perspective on the implementation of BESS.

1.5.1. Literature

The literature review (outlined in Section 2.1) forms a critical component of this research by establishing the methodological foundation and supporting the development of the model's scenarios. Specifically, the review serves two primary purposes: first, to justify the decision to use an optimization model as the primary analytical tool for this research, and second, to identify to what extent systemic considerations influence BESS placement (e.g. technical factors, institutions, etc.), which were further validated through stakeholder interviews.

To find academic and peer-reviewed literature for the formulation of a research gap, a backward snowballing method of key theoretical frameworks have been applied and the Scopus database was used. In Scopus, relevant articles have been obtained by (I) using appropriate keywords and booleans (see Appendix A for detailed description), (II) scoping down on English literature published >2018 and (III) scanning relevancy of the title and the abstract of the research. Here a focus has been laid on literature that examines spatial planning in energy systems. Tables A.3 & A.4 outline the literature that is used.

1.5.2. Interview Approach

In addition to the literature review, a series of semi-structured interviews were conducted with experts within TenneT and BESS developer market parties to gather qualitative insights into the challenges and opportunities surrounding BESS deployment. A total of five interviews were performed during this research. Three of which, within TenneT to acquire knowledge about the process of BESS development and- integration from a TSO perspective. The final two interviews were performed to inform the model which scenarios would be relevant. Furthermore, they were used to gain insight into the real-world applicability of the optimization model. Table 1.1 below provides an overview of the different interviews that were performed.

A purposive sampling strategy was employed to ensure the selection of respondents with diverse roles and expertise, including technical, regulatory, and market perspectives. This approach facilitated the

Table 1.1: Overview of Interviews

Interview index	Department	Expertise	Length of Interview
TenneT Interview 1	ESP-GP-SES	Spatial considerations for placing BESS	31 minutes
TenneT Interview 2	ESP-SI/GP	Battery profiles	22 minutes
TenneT Interview 3	Rights & Environment Management	Land prices	26 minutes
Market Interview 1	Ventoline (external)	BESS integration	57 minutes
Market Interview 2	GIGA-storage (external)	BESS integration	35 minutes

Interview summary reports are available upon request

understanding of the dynamics and decisions influencing BESS deployment (Bryman, 2016).

The interviews were designed to achieve two primary objectives: (1) to inform the development of the optimization model by identifying relevant constraints and exploring plausible scenarios, and (2) to analyze the specific phases of BESS development that impact location decisions. By focusing on key themes such as technological maturity, regulatory frameworks, market dynamics, and land-use considerations, the interviews provided a nuanced understanding of the factors shaping BESS deployment, and are therefore directly linked to answering SQ1. These themes were tailored to the expertise of each respondent, ensuring that discussions remained relevant and insightful.

To maintain methodological rigor, the TU Delft Human Research Ethics Committee (HREC) approval was obtained for the data management plan, informed consent process, and adherence to the HRX checklist. The flexibility of the semi-structured interview format allowed discussions to adapt to the unique knowledge and perspectives of the respondents (Bryman, 2016). For instance, regulatory specialists provided insights into permitting delays and zoning restrictions, while technical experts highlighted challenges related to proximity to HV substations and grid capacity.

The data collected during the interviews was transcribed in full and synthesized into detailed summary reports (available upon request), capturing both direct responses and broader contextual insights. These findings played a key role in defining the variables and constraints used in the optimization model and helped identify key systemic considerations for scenario development. For example, the interviews confirmed the importance of spatial constraints, such as exclusion zones and proximity to infrastructure, as critical factors influencing BESS placement decisions (further outlined in Section 2.2).

A template for the interview questions is provided in Appendix B, offering transparency into the interview process and ensuring replicability.

1.5.3. Modeling Approach

Energy investment models are widely recognized for their ability to evaluate complex interactions between technological, spatial, and economic factors in energy systems. This research employs such a modeling approach to explore the relationship between BESS placement, spatial constraints, and grid expansion investments.

The modeling framework is structured into four key phases, as described by Dam et al. (2013): conceptualization, formalization, implementation, and usage. In the conceptualization phase, critical components, relationships, and constraints are identified, alongside the data inputs required for the analysis. These include both BESS-related parameters (e.g., spatial constraints and economic land costs) and grid-related parameters (e.g., transmission line capacities and HVDC interconnections). During the formalization phase, these components are translated into mathematical formulations solvable within the PyPSA-Eur model, ensuring that the interdependencies between BESS and line expansion decisions are explicitly accounted for. The implementation phase defines the scenarios and temporal snapshots used in this study, while the usage phase focuses on interpreting the model outputs and validating their reliability.

The study analyzes two temporal snapshots, 2023 and 2040, to capture both the current state of the HV grid and a future system characterized by higher renewable penetration, increased electricity demand, and stricter decarbonization targets. These snapshots provide distinct points of reference to evaluate system dynamics, including the relative reliance on BESS versus grid expansion under different conditions. The 2023 network reflects the as-is system configuration, while the 2040 network offers a projected scenario incorporating anticipated changes in energy policy and demand. By comparing these perspectives, the model sheds light on how evolving grid requirements and renewable energy integration influence both BESS placement and transmission planning.

Each temporal snapshot is further divided into three scenarios designed to evaluate the effects of spatial and economic constraints. The BASE scenario assumes no significant constraints, providing a reference for cost-optimal deployment under ideal conditions. The COL scenario incorporates economic considerations, such as regional land costs, while the EXCL scenario applies strict spatial restrictions based on exclusion zones. By incorporating these scenarios, the model assesses how spatial and economic factors influence not only BESS configurations but also the extent to which grid expansion is required to address residual flexibility needs.

In this model, parameters (inputs) include system-wide technical constraints (e.g., grid topology, transmission capacities, renewable generation profiles), spatial exclusions, and economic data such as land costs. These inputs are fixed for each scenario and temporal snapshot. On the other hand, decision variables (outputs) include BESS placement (capacity and location) and grid expansion investments, which are optimized to minimize total system costs while adhering to the defined constraints. This distinction ensures clarity in how the model processes data and generates results.

The inclusion of line expansion in the model was initially unintentional, as it stemmed from the default functionalities of the PyPSA-Eur framework. However, it soon became clear that analyzing both BESS deployment and grid expansion together offers valuable insights into the trade-offs and complementarities between these flexibility options. This dual analysis is particularly relevant for TenneT's planning processes, which must consider how spatial constraints and infrastructure investments jointly impact system costs and resilience.

While grid expansion was not the primary focus of this research, its inclusion as a decision variable enables the model to capture the interplay between BESS deployment and network reinforcements. This is especially critical in constrained scenarios, where limited spatial availability for BESS may increase reliance on grid expansion. By integrating both flexibility measures, the model provides a more comprehensive understanding of how spatial and economic factors influence the overall design of the energy system.

This modeling approach directly supports the research objectives by focusing on how spatial constraints and land-use considerations affect BESS placement, as outlined in Sub-questions 2 and 3. Additionally, the interplay between BESS deployment and line expansion, though not the primary focus of the research, offers valuable insights into the broader implications of these flexibility measures for grid planning. This dual perspective ensures that the findings are both academically robust and practically relevant, particularly for TenneT's long-term strategies.

1.5.4. Mixed-Method Approach

An embedded mixed-methods approach combining qualitative insights with quantitative modeling and simulation has been chosen. The quantitative and qualitative data are collected simultaneously, but the qualitative data is embedded within the quantitative data. This design is best used when you want to focus on the quantitative data but still need to understand how the qualitative data further explains it (Bryman, 2016). This dual approach allows for the understanding of the socio-technical dynamics influencing BESS deployment and facilitates the development of a robust optimization model (Dam et al., 2013).

The literature review establishes the need for a spatially explicit optimization model, identifying key factors such as spatial constraints and economic considerations. These insights shape the model's parameters, including exclusion zones and proximity requirements, and guide scenario selection.

Expert interviews complement the literature by providing qualitative insights into socio-technical and economic constraints. Stakeholders from TenneT and the BESS sector validated assumptions, highlighting practical barriers like permitting delays and operational feasibility, ensuring the model aligns with real-world conditions.

The optimization model integrates these insights to quantify the impact of spatial and economic constraints on BESS placement. It evaluates trade-offs across scenarios, with results contextualized through literature and interviews, ensuring a comprehensive socio-technical interpretation.

Throughout the research process, the qualitative and quantitative approaches work together in an iterative way. Insights from the literature and interviews inform the model design and scenario selection, while the model results feed back into the interpretation of qualitative findings. This integration ensures a robust analysis that aligns theoretical knowledge with practical applicability, supporting the development of actionable insights for BESS deployment in the Dutch HV grid. Figure 1.2 represents the visualization of the method described above.

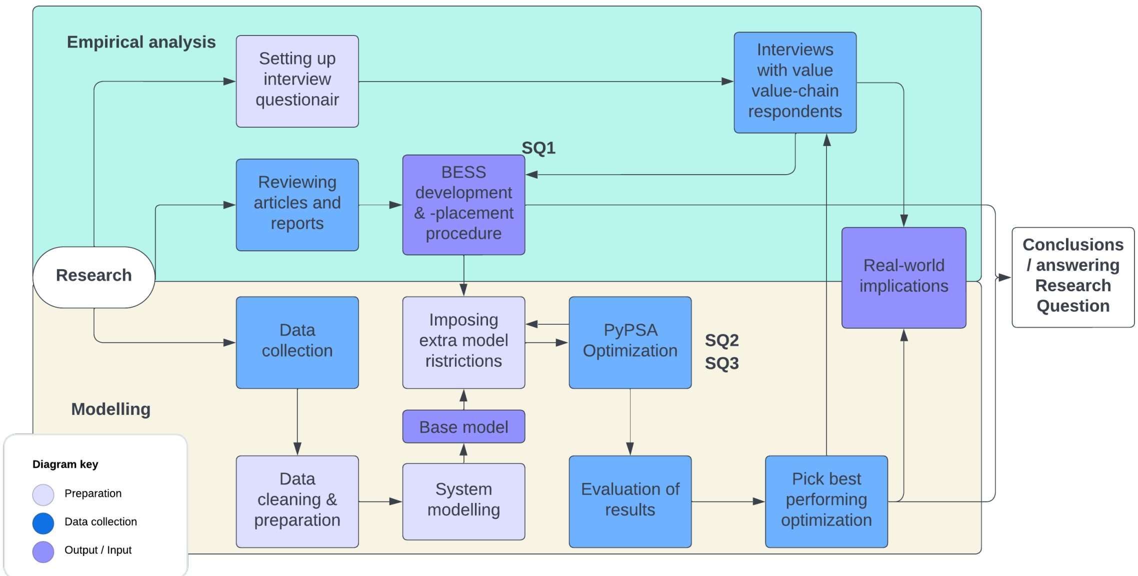


Figure 1.2: Research flow diagram

1.6. Link to CoSEM Master Program

The research conducted in this thesis aligns strongly with the CoSEM Master program's focus on complex socio-technical systems (STS). The energy sector, and specifically the deployment of BESS, shows the relation between actors, technologies, and institutional frameworks that define such systems. This thesis directly applies CoSEM principles by examining the interconnected nature of the energy transition, where technological solutions like BESS are shaped by infrastructure, regulations, and diverse stakeholder interests.

The stakeholder interviews conducted in this study revealed how diverging priorities influence BESS placement. TSOs focus on grid stability and congestion management, while private developers prioritize cost efficiency and regulatory clarity. These perspectives informed the modeling constraints and provided practical insights into the socio-economic factors impacting deployment.

The Dutch electricity grid operates within a complex institutional environment where land-use regulations, zoning policies, and climate targets play critical roles. By integrating constraints such as exclusion zones and land costs into the model, this research aligns with the institutional and spatial planning considerations highlighted by the PEH. Exclusion zones, which account for areas where BESS cannot be developed due to competing land uses or regulatory restrictions, reflect the challenges of balancing energy infrastructure development with broader spatial and environmental policies. Similarly, incorporating land costs introduces an economic dimension to site selection, ensuring that the model not only optimizes for technical efficiency but also reflects the financial realities faced by developers and policymakers. These constraints bridge the gap between theoretical optimization approaches and the practical, multi-dimensional realities of BESS deployment, making the results more relevant and actionable for real-world applications.

The multi-disciplinary methodology not only bridges the technical and socio-economic dimensions of BESS deployment but also emphasizes the practical application of CoSEM tools to address real-world challenges. Ultimately, this work reflects the program's aim of equipping researchers to navigate and guide transitions within complex systems like the energy sector.

1.7. Thesis Outline

This thesis is structured to systematically address the challenges and opportunities surrounding the optimal placement of Battery Energy Storage Systems in the Dutch high-voltage grid. The following chapters provide a clear narrative of the research process, findings, and implications:

Chapter 2: Literature Review and Interview Analysis
Reviews state-of-the-art academic literature to justify the use of spatially explicit optimization models for BESS placement. Additionally, this chapter synthesizes insights from interviews with key stakeholders, including TenneT and market participants, to understand real-world considerations and processes influencing BESS deployment. The findings from this chapter shape the scenarios and parameters used in the modeling approach.

Chapter 3: Model Methodology
Details the research methodology, including the selection of the PyPSA-Eur modeling framework and its integration with spatial and economic constraints. This chapter explains the data collection process, scenario design, and the iterative modeling approach, ensuring alignment with both theoretical and practical considerations.

Chapter 4: Case Study
Focuses on the application of the PyPSA-Eur model to the Dutch HV grid. It describes the network configurations for the years 2023 and 2040, outlines the input data and assumptions, and explains the scenarios analyzed to explore the impacts of spatial and economic constraints on BESS placement.

Chapter 5: Results
Presents the optimization model results, focusing on spatial distribution, system costs, congestion management, and line utilization. This chapter provides a detailed comparison of the three scenarios (BASE, COL, and EXCL) for both 2023 and 2040, offering insights into the effects of spatial constraints and land costs.

Chapter 6: Discussion
Interprets the results in the broader context of energy system planning and policy. It reflects on the interplay between spatial, economic, and technical factors, discusses the implications for stakeholders, and evaluates the robustness of the modeling approach and assumptions.

Chapter 7: Conclusion and Recommendations
Summarizes the key findings of the research, addresses the research questions, and outlines the implications for policy and practice. This chapter also provides recommendations for future research and reflects on the learning process during the study.

Each chapter builds on the previous one, ensuring a cohesive exploration of the optimal placement of BESS in the Dutch HV grid while addressing the main research question and sub-questions.

2
Literature Review & Interview Analysis

To answer the research questions, this research aims to uncover the impact of spatial constraints and economic land-use considerations on optimal BESS placement. In this chapter, the academic literature surrounding spatial planning in energy systems is first reviewed (Section 2.1). This review aims to: 1) explain why a model is an appropriate tool for tackling these types of problems, 2) explain what criteria are considered for the model selection, and 3) justify decisions for scenario selection. Furthermore, Section 2.2 describes the interview analysis resulting in the process description of BESS development and -integration in the Dutch electricity grid, along with their components, and characteristics. This information addresses sub-question 1 on optimal BESS placement by identifying constraints and key factors that influence placement decisions. Furthermore, it informs the decision on relevant scenarios for the power model described in Chapter 3. Finally, Section 2.3 draws conclusions about the relevant findings in this chapter.

2.1. literature Review: Spatial Planning in Energy Systems

The optimal placement of Battery Energy Storage Systems (BESS) is influenced by a combination of technical, financial, and geographical constraints, all of which must be considered to ensure cost-effective and spatially feasible deployment. Existing research highlights the increasing importance of energy storage in grid stabilization and flexibility but also underscores key gaps in spatial planning approaches that account for real-world land-use constraints and economic considerations. This literature review serves three primary purposes:

1. **Justification for an Optimization Model** – It establishes why an optimization-based approach is necessary for evaluating BESS placement, particularly given the spatial constraints and infrastructure requirements of the Dutch HV grid.
2. **Defining Key Model Components** – It identifies the essential elements of a BESS placement model, emphasizing the need for a financial objective function, technical constraints, and spatial restrictions. It also evaluates the relevance of institutional factors in BESS deployment, concluding that while regulatory frameworks influence spatial planning, no clear regulations currently govern BESS siting in the Netherlands, aside from safety standards such as PGS-37-1, which are discussed further in Appendix D.
3. **Justification for Scenario Selection** - It justifies the choice for the land cost-, and exclusion scenario used in the modeling analysis.

The insights gained from this literature review directly inform the methodological choices in Chapter 3, particularly the selection of modeling constraints and scenario development, and also help frame the expert interviews.

2.1.1. Justification for a Spatially Explicit Optimization Model

Energy system planning has traditionally relied on optimization models to evaluate the cost-effectiveness of infrastructure investments. However, many of these models focus primarily on economic and technical feasibility while neglecting the spatial constraints that significantly impact real-world deployment (Venkateswaran et al., 2020; N. Wang et al., 2020).

In spatially constrained environments such as the Netherlands, BESS placement must account for land availability, exclusion zones, and proximity to critical grid infrastructure, making spatially explicit modeling essential. Studies such as N. Wang et al. (2020) and Luo et al. (2023) emphasize that failing to incorporate spatial constraints leads to infeasible deployment strategies, highlighting the need for a model that integrates geographical barriers while optimizing system-wide costs.

2.1.2. Essential Components of a Spatially Explicit BESS Model

To find the essential components needed to model BESS locations, academic literature is compared to find which systemic characteristics are commonly used for these analyses. Aside from identifying key components of spatially explicitly modeling in existing literature, this analysis aims to further delineate the scope. An overview of this comparison is given in table 2.1.

First of all, financial feasibility is a major determinant in BESS investment decisions. Many studies incorporate capital expenditures (CAPEX), operational expenditures (OPEX), and market revenues into optimization models to assess cost-optimal storage deployment (Cole et al., 2021; Schmidt & Staffell, 2023).

Secondly, the placement of BESS must align with technical constraints to ensure efficient grid integration and operational feasibility. Key considerations include grid connection capacity, power flow limitations, and network congestion management, all of which influence the effectiveness of BESS in supporting grid stability (Venkateswaran et al., 2020). Studies emphasize that failing to incorporate these constraints can lead to misplaced storage solutions that do not alleviate congestion or optimize system flexibility (J. Wang et al., 2022).

To address these challenges, the optimization model in this study must be highly adaptable and capable of integrating large datasets, including transmission network topology, power flow constraints, and renewable energy generation profiles. Additionally, given the extensive data requirements for grid-scale calculations and the constrained time frame of this research, computational efficiency is crucial. The model must be capable of handling large datasets while ensuring that scenario analyses remain scalable and computationally feasible within the available time. The model must allow for scalable scenario analysis without excessive computational overhead. Furthermore, previous studies highlight the importance of choosing models that balance adaptability with efficiency. For example, Luo et al. (2023) stress the necessity of models that can process large-scale datasets while maintaining time-efficient computations, particularly when analyzing the interactions between BESS and network expansion. By incorporating grid constraints and maintaining model scalability, this study ensures that the optimization framework realistically reflects the technical feasibility of BESS deployment while remaining practical for use within the study's time constraints.

Furthermore, land-use restrictions and zoning regulations significantly impact the feasibility of BESS deployment. Studies incorporating geo-spatial analysis, such as N. Wang et al. (2020) and Zhang et al. (2023), emphasize the importance of explicitly incorporating spatial exclusion zones into optimization models. Factors such as NATURA2000 protected areas, urban expansion zones, and agricultural land-use conflicts can limit siting opportunities and influence the cost-effectiveness of storage solutions. The model used in this thesis integrates these geographical constraints through exclusion zones and grid proximity considerations, ensuring that site selection aligns with both technical feasibility and spatial planning priorities.

Finally, institutional factors, such as permitting processes and policy frameworks, influence BESS deployment by shaping spatial planning decisions and market participation rules. Some studies attempt to integrate regulatory constraints into energy system models, but they often struggle with regional variations in policies, making it difficult to standardize institutional considerations at a national level (Hameed et al., 2021; Pedersen et al., 2021).

Table 2.1: Review of relevant literature on spatial planning in energy systems

Reference	Study Type/Field	Spatial Coverage	Institutional factors	Geographical factors	Financial factors	Tech-factors	Additional Information
Lombardi et al., 2020	SPORES method for RE planning	Italy (regional and national)	X	X	X	X	Introduces the SPORES method for exploring spatially explicit, practically optimal renewable energy configurations; considers socio-political trade-offs.
Luo et al., 2023	DN Network Planning Model	China (general context)		X	X	X	Highlights the importance of seasonal demand variability and grid constraints for energy storage planning.
Settou et al., 2021	GIS-AHP Solar PV site selection	Algeria		X	X	X	Demonstrates the adaptability of GIS-based methodologies to evaluate land-use constraints and select optimal sites.
Venkateswaran et al., 2020	BESS Degradation Modeling	IEEE-33 Node System (theoretical)			X	X	Focuses on resilience and reliability under dynamic conditions, with an emphasis on BESS degradation modeling.
N. Wang et al., 2020	Power system planning	Netherlands	X	X	X	X	Emphasizes the role of spatial and economic factors in capacity planning, particularly in spatially constrained contexts like the Netherlands.
J. Wang et al., 2022	Location and Capacity Planning for Energy Storage	China			X	X	Highlights spatial and economic factors for optimal energy storage capacity planning.
Zhang et al., 2023	Multi-objective Optimization for BESS and Renewable Energy	China (theoretical context)			X	X	Integrates capacity degradation and demand response into energy storage planning to minimize expenditures.
Zhou et al., 2022	Large-scale Grid-Connected Renewable Energy	China (regional grid)			X	X	Highlights the importance of spatial and economic factors in large-scale grid planning and energy storage.
Pedersen et al., 2021	Modeling All Alternatives (MAA) for Renewable Energy Planning	European Energy System	X	X	X	X	Develops the MAA approach, which systematically identifies all near-optimal solutions rather than a single cost-optimal one. This ensures spatial, socio-economic, and political feasibility in renewable energy planning by accounting for diverse implementation pathways.
Hameed et al., 2021	Business-Oriented BESS Placement	Bornholm (Denmark)	X	X	X	X	Emphasizes how BESS feasibility depends on land availability, grid integration costs, and location-specific grid services. Demonstrates how spatial constraints directly impact technical and economic viability, making it a key factor in energy system planning.

In the Netherlands, no clear regulations currently exist regarding the spatial allocation of BESS beyond general safety standards. The Dutch PEH acknowledges this regulatory gap and highlights the lack of spatial planning frameworks specific to BESS deployment (RVO, 2024a). The only existing standard, PGS-37-1, provides safety guidelines but does not regulate where BESS can or cannot be placed. Given this regulatory landscape, this thesis does not explicitly model institutional constraints, as their inclusion would require regionalized policy assumptions that lack standardization. Instead, regulatory insights are incorporated qualitatively through expert interviews, while further discussion on PGS37-1 is provided in Appendix D. An additional regional analysis was performed based on provincial BESS reports to identify potential differences in regional policies as these might impact the analysis. Since institutions are not considered these results are discussed in Appendix D.3 and serves as additional information and base for further studies.

Table 2.1 summarizes key factors considered in spatial planning literature Notably, all articles mention financial and technical factors in relation to spatial planning in energy systems. Nearly all articles also consider geographic factors such as land-availability to study spatial planning in energy systems. To demarcate this study, these three systemic characteristics will be taken into account, leaving institutional factors out of the scope of this research.

2.2. Interview Analysis

To gain a better understanding of the development and placement of BESS, this research conducted expert interviews with key stakeholders involved in the process. The question form used for the expert interviews within TenneT and external market parties can be found in appendix B.

The primary goal of these interviews was to inform the modeling approach by identifying real-world constraints and challenges in BESS deployment. Specifically, the interviews aimed to:

1. **Map the BESS development process** – Identify the procedural steps from site selection to grid integration (answering SQ 1).
2. **Analyze location-sensitive barriers** – Examine how different phases of BESS development interact with spatial decision-making barriers, including regulatory, technical, and economic challenges. This includes identifying key actors such as municipalities, landowners, and grid operators, whose decision-making influences location feasibility
3. **Support scenario development** – Validate assumptions for the EXCL and COL scenarios used in the optimization model.

As described in the research approach, a total of five semi-structured interviews were conducted with experts from TenneT (3 interviews) and market parties (2 interviews) to ensure a balanced perspective. These discussions provided insights into technical, economic, and regulatory considerations that influence BESS placement in the Dutch HV electricity grid.

The findings from these interviews were translated into an 18-step process description of BESS development and -placement. These steps were then analyzed to distill the phases that impact the decision for BESS allocation. Although it would be most relevant to include all of these phases in the model setup, a combination of time-feasibility constraints and relevance to this study justify further filtering. The remaining phases are then used as scenarios for the optimization model described in Chapter 3. This interview analysis was crucial in shaping the model's scenario constraints, particularly regarding land costs (COL scenario) and proximity limitations (EXCL scenario).

In the following subsections, we first describe the BESS development process as derived from expert input. We then provide a detailed discussion of interview findings, followed by a comparative analysis with literature to contextualize key insights. Finally, we conclude by outlining the prioritization of process steps for modeling considerations.

2.2.1. BESS development procedure

To determine the optimal placement of large-scale BESS in the Dutch HV electricity grid, it is necessary to analyze the full development and placement process. By uncovering this process mainly from the perspective of market parties (BESS developers) and additional insights from TenneT, this section answers Sub-question 1 (SQ1):

"What are relevant considerations in the process of BESS development and placement according to academic literature and real-world experts in the Netherlands?"

By understanding how BESS projects are planned and executed, this section identifies key process steps and variables that significantly influence spatial decision-making and determines which of these should be incorporated into the optimization model. The findings from the interviews were synthesized and validated with literature to provide an 18-step structured process description broken down into 6 phases. For the scope of this research, which extends to 2040 as the farthest temporal horizon, only phases up to and including commercial operation are considered. Consequently, the end-of-life (EoL) phase, including decommissioning, repurposing, or recycling of BESS, falls outside the scope of this study.

1. **Battery Manufacturing**

Step 1: Source Raw Materials Description: Batteries, particularly lithium-ion, require raw materials such as lithium, cobalt, and nickel. These materials are primarily sourced from global suppliers, with a growing interest in developing European supply chains [market interview 2].

Step 2: Battery Assembly and Quality Assurance Description: Batteries are assembled into cells, modules, and finally into battery packs. Quality assurance is conducted to ensure cells meet performance, safety, and lifespan criteria [market interview 2].

2. **Initial Project Planning and Site Selection**

Step 3: Market Research and Feasibility Study Description: Identify market opportunities, revenue streams (arbitrage, ancillary services, etc.), and technical requirements. Feasibility studies assess project location, cost, and market demand (Schmidt & Staffell, 2023).

Step 4: Site Identification Description: Identify potential sites for BESS placement. Sites near substations or generation sources are prioritized to reduce grid connection costs. Key Considerations: Avoid ”no-go” zones (e.g., NATURA2000 areas), consider zoning regulations (e.g., agricultural to industrial land conversion), and prioritize areas near high-voltage stations [TenneT interview 3, market interview 1, (N. Wang et al., 2020)]

Step 5: Land Acquisition Description: Acquire the selected site, which may involve purchase, lease, or expropriation. Agricultural land often requires rezoning, which can be time-consuming [TenneT interview 3].

3. **Permitting and Regulatory Compliance**

Step 6: Spatial Planning and Zoning Compliance Description: Apply for zoning changes to convert agricultural land into industrial land (if applicable) [tenneT interview 3] Challenges: Zoning changes require provincial approval, and projects may face opposition from local stakeholders (RVO, 2024a).

Step 7: Environmental and Safety Assessments Description: Conduct environmental impact assessments (EIA) to assess the effects on ecology, water, noise, and nitrogen emissions Requirements: Compliance with national policy (RVO, 2024a; TenneT, 2024d)

Step 8: Obtain Required Permits and Approvals Description: Obtain construction and operational permits from municipalities, provinces, and national authorities. Stakeholder engagement is essential during this phase [TenneT interview 3, market interview 1]

4. **Technical Design and Engineering**

Step 9: Engineering Design Description: Develop technical designs for site layout, BESS capacity, interconnections, and safety systems (e.g., fire protection)[TenneT interview 1, market interview 2]

Step 10: Grid Connection Application Description: Submit a grid connection request to TenneT. The request must specify power capacity, voltage levels, and location [TenneT interview 2] Challenges: High costs, lengthy approval times, and possible congestion issues [market interview 1]

Step 11: Technical Compliance with TenneT Requirements Description: Design BESS to meet technical grid requirements for reactive power, fault ride-through, and frequency support [TenneT Interview 2] (TenneT, 2024d)

5. **Procurement, Installation, and Commissioning**

Step 12: Procurement of Components Description: Purchase batteries, inverters, converters, and transformers. Transformers may have long lead times due to supply chain issues [market interview 2]

Step 13: Site Preparation Description: Prepare the site by clearing land, pouring concrete foundations, and installing infrastructure like cables and underground conduits [market interview 2]

Step 14: Installation and Assembly Description: Install battery modules, inverters, and other components. Local contractors and engineering teams are often used to reduce logistics complexity [market interview 2]

Step 15: Testing and Commissioning Description: Conduct testing to ensure operational safety and technical compliance. This includes fault-ride-through testing, reactive power capabilities, and system stability assessments [TenneT interview 2]

6. **Commercial Deployment and Operation**

Step 16: Business Model Development Description: Finalize the commercial strategy, which could involve revenue stacking (e.g., arbitrage, capacity market, balancing services) (Schmidt & Staffell, 2023; TenneT, 2024d).

Step 17: Contracting and Market Participation Description: Register to participate in the Dutch capacity market or ancillary service markets, such as frequency containment reserves (FCR) (TenneT, 2024d)

Step 18: Operational Management and Maintenance Description: Manage the BESS remotely, ensuring adherence to market participation rules and handling ongoing maintenance (TenneT, 2024d)[market interview 2].

To ensure that the insights from the BESS development process are effectively incorporated into the optimization model, it is essential to establish how each step interacts with the modeling framework. The spatial components in this process—such as site selection, land acquisition, zoning compliance, and environmental assessments—represent key constraints that directly influence the optimization scenarios (BASE, COL, and EXCL). These constraints define the spatial feasibility of BESS placement and serve as input parameters for the model. Moreover, the decision-making sequence outlined in this section highlights critical points where the model can be applied. In early planning phases, the model can function as an exploratory tool to assess potential locations based on spatial and economic feasibility. In later stages, it can be used as a validation mechanism to test whether selected sites align with optimal grid stability and cost-efficiency criteria. This structured integration ensures that the conclusions drawn from the optimization results remain closely tied to real-world BESS development trajectories

From these process steps, a filtering can be made on steps that are location-dependent. Those steps are most relevant for this research since it can help in understanding the selection of locations for BESS. This knowledge could aid policymakers in steering the system to a more optimal configuration, and aid TSOs in making region-specific projections of BESS allocation. Table 2.2 provides an overview of each process step alongside its respective impact on BESS location decision-making.

Table 2.2: BESS Development and Placement Process Steps

Step No.	Phase	Description	Impact on Location Decision?
1	Battery Manufacturing	Source raw materials (e.g., lithium, cobalt)	No, as raw materials are globally sourced.
2	Battery Manufacturing	Assembly and quality assurance of battery packs	No, as this occurs at manufacturing facilities.
3	Initial Planning	Conduct market research and feasibility studies	Partially, as market demand and location viability are assessed.
4	**Site Selection**	Identify potential sites near substations or generation sources	Yes, as proximity to infrastructure reduces grid connection costs. The closer BESS can be built to a station the more attractive.
5	**Land Acquisition**	Acquire or lease land and address rezoning requirements	Yes, as land availability and zoning significantly influence placement. Cheap land that requires no rezoning is more attractive.

Step No.	Phase	Description	Impact on Location Decision?
6	**Zoning assessment**	Ensure spatial planning and zoning compliance	Yes, as zoning regulations impact site eligibility. Zones that require more complex planning are less attractive.
7	**Environmental Assessment**	Assess impacts on ecology, noise, and emissions	Yes, as environmental considerations may rule out certain locations. The environment must be suitable for BESS placement.
8	**Permitting**	Obtain required permits and stakeholder approvals	Yes, as permits are location-specific and depend on local policies. The plans must comply with policy standards.
9	Technical Design	Develop site layout and BESS capacity plans	Partially, as location-specific technical designs may be required.
10	Grid Connection	Apply for grid connection with TenneT	No, as connection costs and congestion do not vary by location.
11	Technical Compliance	Ensure compliance with TenneTs technical requirements	No, as compliance is uniform across locations.
12	Procurement	Procure batteries and components	No, as procurement is independent of location.
13	**Site Preparation**	Prepare site with necessary infrastructure	Yes, as site conditions impact preparation work. The more preparation a site requires, the less attractive it is.
14	Installation	Install battery modules and components	No, as installation processes are standard.
15	Testing	Conduct testing for compliance and safety	No, as testing is independent of site.
16	Commercial Deployment	Develop business models and revenue strategies	No, as business strategies are market-focused, not location-specific.
17	Market Participation	Register for capacity or ancillary service markets	No, as registration is not tied to specific locations.
18	Operations	Manage BESS operations and maintenance	No, as operational management is generally remote.

Building on this process description, the interviews further aimed to understand which steps form bottlenecks for the effective placement of BESS.

As summarized in Table 2.2, several process steps incorporate regionally dependent elements. These include: site selection, land acquisition, environmental assessment, permitting, technical design, and site preparation. These steps are considered especially relevant to this study as they give insight into real-world decision-making processes that influence BESS placement. Moreover, when market dynamics show significant misplacement of BESS resulting in high system costs, policymakers should prioritize addressing these steps.

From these six phases relevant to spatial decision-making for BESS, final filtering is performed based on TenneTs prioritization, time considerations, and findings from the literature review.

Namely, institutional types are not considered as was explained in the literature review section, due to their highly regional characteristics and limited time resources (environmental assessment and permitting). The impact of BESS site preparation and its technical design on location decision-making them difficult to quantify. In consultation with TenneT, these phases are therefore also not included. Future

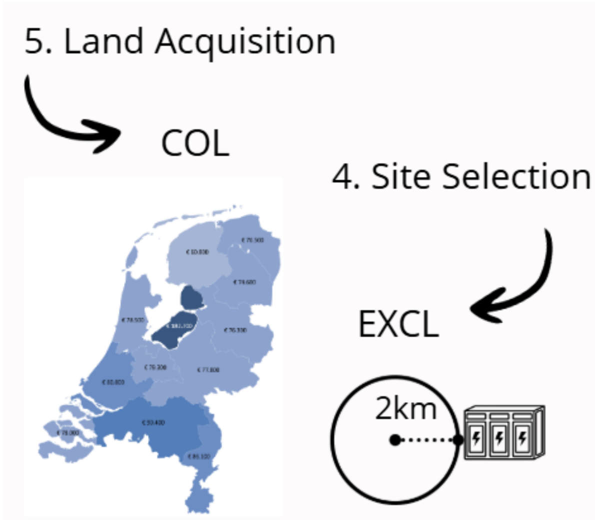


Figure 2.1: Scenario Selection from BESS Development Phases (adapted from Kadaster (2024))

research could dive deeper into the quantification- and inclusion of these phases in models. Table 2.3 visualizes which phases are thus considered for the scenarios.

Table 2.3: Phases Impacting Location Decision and Systemic Types

Phase	Systemic Type	Considered for Scenario Analysis?
Site Selection	Geographical	Yes
Land Acquisition	Financial	Yes
Environmental Assessment	Geographical & Institutional	No
Permitting	Institutional	No
Technical Design	Technical	No
Site Preparation	Technical	No

The selected phases can be implemented and quantified in different ways. However, since the focus of this study lies in identifying the effects of land restrictions on the electricity system, less focus is put on the alternatives to operationalize these restrictions. The exact quantification and implementation of selected phases were determined based on interview insights and consultation with TenneT. Figure 2.1 depicts this process.

Market Interviews 1 and 2 highlighted that BESS developers prioritize sites with minimal grid connection cable costs, favoring locations as close as possible to an HV station within legal limits. A maximum distance of 2 km from an HV station for BESS construction was identified, referred to hereafter as the Exclusion (EXCL) scenario.

Land acquisition for BESS placement is assessed through the application of regionalized land costs. Interview 3 revealed that this process often involves purchasing agricultural land, as it is typically the most spatially suitable and readily available for BESS development, referred to hereafter as the Cost of Land (COL) scenario.

The specific implementation of the variables in modeling scenarios is discussed in sections 3.4, and 4.1.3.

2.2.2. Comparitve Perspectives on BESS placement

After summarizing the full BESS development process, this section focuses on comparing key aspects of BESS placement from the perspectives of TenneT and market parties.

The comparison highlights areas where both stakeholders have an interest and where potential misalignment could affect BESS deployment strategies. The interviews with TenneT focused on the technical, regulatory, and land cost aspects of the integration of BESS into the grid infrastructure. The market interviews emphasized economic feasibility and operational strategies for BESS deployment.

TenneTs Perspective

First of all, the interviews unveiled that TenneT regards the impact of BESS placement on average line loading and peak loading frequency as highly important. Therefore this shall also be considered in the network model analysis.

Aside from this, the interviews with TenneT representatives highlighted the following key aspects:

- **Technical Challenges**: It is important to ensure grid stability through appropriate siting of BESS to reduce congestion and maintain voltage stability.
- **Land Use and Permitting**: Complex permitting processes and the need for zoning changes for agricultural land present significant barriers for swift BESS integration. Furthermore, experts stress that much uncertainty exists about land use plans surrounding HV stations. Difficult trade-offs have to be made for instance when choosing between BESS development or leaving space for potential grid expansions later in the future.
- **Strategic Placement**: HV substations (220/380 kV) are prioritized to minimize congestion and enhance system-wide benefits.
- **Regulatory Constraints**: The absence of a uniform national framework for BESS placement complicates long-term planning. TenneT is not allowed to reject applications for BESS placement at locations (without a good reason) but is responsible for managing potentially additional stress on the grid.

Market Party Perspective

Interviews with BESS developers offered complementary insights:

- **Economic Drivers**: Grid connection costs and permitting delays were identified as more significant barriers than land costs.
- **Market-Driven Placement**: Developers prioritize locations near existing grid infrastructure to reduce cable installation costs.
- **Collaboration Needs**: Developers emphasized the importance of transparency and collaboration with TenneT to align projects with grid priorities.
- **Information Uncertainty**: Market participants must submit BESS project requests to TenneT to obtain a connection to the HV grid. Due to rapid market cannibalization and subsequent profit degradation, they aim to secure grid connections as quickly as possible. As a result, many market participants apply for BESS capacity at multiple HV stations to safeguard their market position. The lack of clarity around optimal BESS allocation creates a scenario where (local) governments delay policymaking, relying on TenneTs allocation assessments. In the meantime, market participants queued for projects face uncertainty about whether future policies will obstruct their initiatives—potentially incurring costs for projects that may later be hindered by regulatory decisions.

Table 2.4 summarizes the key findings for both perspectives. The interviews reveal two contrasting perspectives between market parties and TenneT. Market parties, despite facing significant market uncertainties, prioritize securing a grid connection as quickly and cheaply as possible to avoid missing market opportunities and to stay ahead of potential market cannibalization. Their decision-making is largely driven by short-term financial feasibility and the ability to monetize storage capacity as soon as possible.

In contrast, TenneT takes a more cautious approach to granting grid connections due to uncertainties surrounding future infrastructure planning, the impact of BESS on grid stability, and a lack of clear regulatory frameworks. Given the high volume of BESS connection applications, TenneTs priority is to ensure that new storage projects align with long-term system efficiency rather than short-term market dynamics. This misalignment in priorities introduces challenges in coordinating strategic BESS placement, as market-driven siting decisions may not always align with system-wide optimization objectives.

This finding directly contributes to answering SQ1 by identifying the conflicting decision-making drivers of key stakeholders involved in BESS deployment. It highlights how market actors prioritize cost and speed, while TSOs focus on system stability and long-term grid planning. These insights show the need for a coordinated national strategy, which is a key motivation for this research in bridging the gap between market-driven BESS deployment and system-optimal planning.

Since the grid impact of BESS is a key indicator for TenneT [TenneT Interview 1, 2], this element shall be included in further analysis. Especially in sub-optimal BESS configurations, it can be relevant to observe how the average line loading, and peak load frequency change.

Table 2.4: Summary of Perspectives on BESS Placement

Aspect	TenneT Perspective	Market Party Perspective
Technical Priorities	Minimize congestion; stabilize voltage	Optimize for market operations
Land Use Challenges	Preference for zones further away from substations to leave space for potential expansions or other infrastructure	Flexibility in siting; focus on reducing connection costs and aiming to build as close to a substation as possible
Financial Considerations	Total system costs and the trade-off between grid expansion costs and reduced transport tariffs resulting from contracts (such as ATR85)	Grid connection costs and regulatory delays, furthermore, transport costs and quick permitting are priorities
Regulatory Needs	National framework for uniformity	Clearer guidance on grid priorities and future policies
Collaboration	Essential for long-term planning and zoning alignment	Needed for timely and feasible project development

2.3. Conclusion

To conclude this chapter, this section outlines the most important findings. This chapter explored the key factors influencing the development and placement of large-scale BESS in the Dutch HV grid. The literature review provided insights into the state-of-the-art methodologies for analyzing spatial planning components in energy system planning, emphasizing the need for an optimization model that integrates technical, financial, and spatial constraints. The interview analysis complemented these findings by mapping the real-world decision-making process surrounding BESS deployment. The results show a clear divergence in priorities between TSOs and market parties particularly regarding congestion. While market participants prioritize securing grid connections as quickly and affordably as possible to maintain competitiveness, TSOs remain cautious due to uncertainties in infrastructure planning, regulatory frameworks, and the long-term system effects of widespread BESS deployment. These conflicting priorities underscore the importance of strategic planning in BESS placement, as suboptimal configurations can lead to inefficient grid expansion investments and increased system costs.

A total of 18 process steps were identified in the BESS development trajectory, ranging from site selection to grid integration and BESS operation (excluding EoL as this is out of the temporal scope of this research). The interviews revealed that certain steps, such as site selection and land acquisition, are particularly influenced by spatial and financial constraints. These insights directly informed the scenario selection in the optimization model, ensuring that the model captures the impact of land-use restrictions (EXCL scenario) and regional land cost variations (COL scenario). Moreover, the findings emphasize the necessity of aligning energy system planning with urban development policies to prevent conflicts in land allocation.

By linking the BESS development process to the optimization model, this research ensures that spatial constraints are not just acknowledged but actively integrated into decision-making. The model is most relevant in phases where spatial planning and grid connection considerations dominate, as these factors determine feasible BESS placement while balancing technical and economic trade-offs. This structured approach clarifies when and how the model should be applied—whether as an exploratory tool for potential siting options or as a validation mechanism for policy alignment. Ultimately, this integration strengthens the conclusions drawn from the model, reinforcing its role as a decision-support tool for strategic BESS deployment.

Despite the growing recognition of BESS as a critical flexibility measure, the absence of clear policies regulating their spatial deployment leads to uncertainties for both grid operators and market participants. While some safety regulations, such as the PGS-37-1 standard, exist to address fire safety risks, a comprehensive spatial regulatory framework is lacking. The recently introduced PEH highlights this gap, calling for further research into the spatial implications of large-scale BESS deployment.

In conclusion, this chapter establishes a foundation for the optimization model by identifying key constraints and system variables that influence BESS placement decisions. The findings from both literature and expert interviews provide the necessary input parameters for modeling scenarios, ensuring that the subsequent analyses are grounded in both theoretical rigor and real-world feasibility. The next chapter will detail the methodology used to implement these insights within the PyPSA-Eur framework.

3 Model Methodology

The placement of large-scale BESS in the Dutch HV electricity grid requires a structured analytical approach that accounts for technical, economic, and spatial constraints. Chapter 2 established the challenges associated with BESS deployment, highlighting the absence of clear policies, uncertainties in grid expansion planning, and the influence of spatial limitations. To address these challenges, this chapter presents the methodological framework used to model optimal BESS placement, ensuring that decision-making aligns with grid stability, cost efficiency, and real-world spatial restrictions.

The model aims to:

- Quantify the impact of spatial limitations on optimal BESS placement.
- Evaluate economic trade-offs, integrating regional land costs into the placement strategy.
- Assess system-wide effects, such as grid congestion, peak load frequency, line expansions, and cross-border electricity flows.
- Compare different spatial and economic scenarios (BASE, COL, EXCL) to determine how land-use policies and market incentives influence BESS feasibility and -placement.

The model is designed to provide insights for multiple stakeholders involved in energy system planning. For TenneT and other TSOs, it evaluates how BESS placement influences grid congestion, network expansion requirements, and overall system costs, helping to align storage deployment with long-term grid stability objectives. For policymakers and spatial planners, the model assesses the impact of land-use restrictions on energy infrastructure development, offering a structured approach to integrating spatial constraints into decision-making. For energy system researchers, it serves as a framework for incorporating spatially explicit constraints into power system modeling, ensuring that future studies consider both technical feasibility and real-world spatial limitations.

This chapter first outlines the model selection process, evaluating different energy system modeling frameworks based on their ability to handle spatial restrictions, and system planning requirements in section 3.1. Based on these criteria, PyPSA-Eur is selected as the modeling tool, given its capability to simulate large-scale energy systems with detailed spatial and network representations.

As discussed in the model approach section, the modeling framework is structured into four key phases, as described by Dam et al. (2013): conceptualization, formalization, implementation, and usage. With the model selected, the chapter then focuses on its conceptualization (Section 3.2, explaining the key functionalities of PyPSA-Eur and how it models energy generation, storage, and transmission expansion. A particular emphasis is placed on how the model incorporates spatial constraints, a critical component in determining BESS placement given the Netherlands' limited land availability and strict zoning regulations. While PyPSA-Eur is not explicitly designed for BESS allocation, this study adapts its spatial modeling capabilities to evaluate the impact of land-use restrictions and economic considerations on optimal storage deployment.

The chapter then moves into the formalization (3.3), and implementation & usage (3.4) of the model, detailing how various inputs- such as electricity demand projections, renewable energy generation profiles, grid constraints and -capacity, and financial parameters—are mathematically framed, structured, and used in the model. To assess the influence of spatial and economic constraints, the study evaluates two temporal snapshots (2023 and 2040) and three scenarios (BASE, COL, and EXCL). These scenarios, derived directly from the insights in Chapter 2, allow for a structured analysis of how exclusion zones and regional land cost variations affect BESS placement decisions.

The following sections elaborate on each of these elements in detail, establishing the framework through which optimal BESS placement strategies are analyzed. Finally, Section 3.5 provides the conclusions of this chapter.

3.1. Spatially Explicit Modeling

Power system optimization models are essential tools for analyzing the complex interactions within electricity networks, particularly for assessing system performance, minimizing costs, managing congestion, and incorporating spatial planning constraints (Hörsch et al., 2018). These models provide a structured framework to evaluate the trade-offs between flexibility measures such as grid expansion and energy storage solutions like BESS.

In recent years, the academic focus on energy system models that incorporate BESS has increased, especially in grids with high shares of renewable energy. Most of these models aim to minimize system costs while balancing supply and demand. However, a key limitation in many of these studies is the underrepresentation of spatial constraints—such as land availability, regulatory zoning, and grid accessibility—that significantly affect BESS deployment (N. Wang et al., 2020).

For this thesis, spatial constraints are defined as the limitations on land availability and suitability for BESS deployment. This includes factors such as proximity to substations, competing land uses, and regulatory exclusion zones. Unlike some models where users predefine potential BESS sites, the approach in this study allows the model to determine optimal locations based on economic and technical feasibility while incorporating geographic restrictions. This ensures that siting decisions reflect realistic spatial constraints rather than being predetermined by the user.

Chapter 2 established the need to integrate technical, geographical, and financial constraints into BESS placement analysis. In response, this model incorporates land costs and exclusion areas to assess their impact on system-wide efficiency and cost distribution. Given the Netherlands' constrained land availability, these factors play a crucial role in ensuring that BESS placement strategies are not only theoretically optimal but also practically feasible. Similar to the challenges faced in VRES deployment, land constraints can significantly influence the spatial distribution of BESS, yet they are often overlooked in existing models. This assessment can lead to overly optimistic placement projections that may not be feasible in real-world conditions, not necessarily due to a complete lack of land availability, but because high land costs and regulatory constraints may render certain locations economically unviable for BESS deployment.

By integrating spatial exclusions and economic land-use considerations into the optimization model, this research addresses the gap in current BESS modeling approaches. This approach ensures that BESS placement aligns with realistic grid constraints and policy objectives, supporting long-term planning for the Dutch high-voltage electricity system.

3.1.1. Model Comparison

Several studies have developed power system optimization models capable of including BESS placement. This section describes several of these studies and compares them on dimensions such as their spatial and temporal coverage & -resolution. The performed model comparison was based on the work by Deng and Lv (2020) which analyzes- and compares different power system models. The result is visualized in overview table 3.1 below.

Firstly, Castro and Espinoza-Trejo (2023) proposed a model to optimize BESS integration in electricity grids with high PV penetration, employing an energy time-shifting strategy to enhance flexibility.

Kazemi and Ansari (2022) took a broader approach by combining BESS placement with transmission expansion planning and security analysis. Their model includes multiple contingencies, such as N-1 and N-2 security events, to examine how different BESS sizes can optimize both cost and system reliability. Although comprehensive, that model does not fully address the impact of spatial factors on BESS deployment, particularly the land requirements for large-scale installations. In contrast, models like the Greenfield Renewables Investment Model (GRIM) by N. Wang et al. (2020) have incorporated spatial data in their approach, specifically for renewable energy investments. GRIM uses geographic and land-use data to identify suitable regions for renewable energy projects within the Dutch grid. Another example is the PyPSA-Eur model by Hörsch et al. (2018), which integrates spatial constraints such as land-use restrictions by utilizing data from OpenStreetMap. Although these models primarily focus on renewable energy, their spatially explicit methodology provides a useful foundation that can be adapted to BESS placement.

Calliope, an open-source energy system modeling framework, can be used for spatially explicit energy system planning, enabling multi-scale modeling that balances spatial resolution and computational efficiency (Pfenninger & Pickering, 2018). It is designed to optimize capacity expansion and dispatch decisions while integrating renewable energy sources, storage, and transmission infrastructure. Calliope's flexibility in defining spatial and temporal resolution makes it a valuable tool for exploring regional and national energy planning scenarios. However, while it can incorporate land-use constraints and spatial exclusions, its primary focus is not on detailed power flow modeling or transmission grid constraints, making it less suited for studies requiring explicit grid-based optimization of BESS placement within high-voltage network operations.

Another framework, the Power Dispatch & Flexibility model, has been developed to evaluate storage and grid flexibility in response to renewable integration (Biancardi et al., 2024). This model emphasizes the economic relation between battery storage and interconnection capacity, offering a valuable perspective on how BESS can complement or substitute for traditional transmission infrastructure. While the model highlights the role of BESS in system balancing, it does not explicitly incorporate spatial land-use constraints, limiting its applicability for geo-spatially explicit planning.

Additionally, Kijak and Gashi (2024) introduce a strategic-level conceptual model that integrates BESS across its full lifecycle—covering planning, design, manufacturing, operation, and maintenance—by aligning international standards such as IEC and ISO 55001. This framework emphasizes dependability and long-term system reliability but lacks the optimization functionalities necessary for evaluating cost-minimal BESS placement within a power system.

Although studies such as those by Damian and Wong (2022), Barla and Sarkar (2023), Wong, Ramachandaramurthy, Walker, et al. (2019), and Wong, Ramachandaramurthy, Taylor, et al. (2019) also model optimal BESS locations and sizing, these models are focused on the distribution system network. This study contrarily focuses explicitly on the transmission system network (since only this lies within TenneTs scope), for which these models are not considered in the comparison.

Building on the insights gained from Chapter 2, the selection of a suitable modeling framework for this research considers both the technical and spatial constraints identified. The interview findings emphasized the significance of proximity to high-voltage stations, grid congestion management, and land use conflicts. Literature highlighted the necessity for a model capable of integrating both technical grid parameters and land-use constraints. Furthermore, in coordination with TenneT, it was decided to focus on a model that is able to capture long-term investment decision. Therefore, PyPSA, GRIM, and Calliope were initially evaluated as potential candidates.

3.1.2. Criteria for model selection

Selecting the appropriate energy system modeling framework for BESS placement optimization requires evaluating key criteria aligned with the research objectives and constraints identified in Chapter 2. The selected model must be capable of integrating technical, financial, and spatial constraints while remaining computationally efficient and transparent. The selection of criteria was guided by literature, expert interviews with TenneT and market parties, and the necessity to address the research questions defined in Section 1.3.

Table 3.2 summarizes the criteria used for model selection, outlining their relevance to both theoretical and practical aspects of BESS deployment modeling. This subsection provides further justification for

Table 3.1: Overview of Power System Models

Reference	Model Name	Time Horizon	Time Steps	Spatial Coverage	Spatial Resolution	Assessment Criteria	Additional Information
Castro and Espinoza-Trejo, 2023	Optimal BESS Placement Model	24-hour daily	Hourly	IEEE 5-bus, 24-bus, 118-bus systems	Not specified	Power loss reduction, voltage stability, optimal BESS placement	Focuses on high PV penetration scenarios; utilizes energy time shift strategy for BESS
Kazemi and Ansari, 2022	Transmission Expansion Planning (TEP) and BESS Placement Model	10-year planning horizon	One-hour time resolution	IEEE 24-bus test system	11 generators, 37 branches, multiple contingencies	Security analysis (N-1), reliability evaluation (N-2), minimizing EENS, cost optimization	Considers 3 BESS sizes (10 MW-10 MWh, 20 MW-20 MWh, 30 MW-30 MWh)
Pfenninger and Pickering, 2018	Calliope	Flexible (from hourly to multi-year)	Variable (hourly, daily, etc.)	Flexible	User-defined (from coarse to fine-grained)	Energy system cost, emissions, resource use, demand satisfaction	Open-source, highly flexible, supports multiple energy technologies, integrates spatial and temporal granularity
N. Wang et al., 2020	Greenfield Renewables Investment Model (GRIM)	Flexible (up to 100% RES target)	Hourly	The Netherlands	30 regions	Minimization of total annualized cost, optimal distribution of RES technologies	Spatially explicit, considers VRES, storage potentials, and land-use limitations
Hörsch et al., 2018	PyPSA-Eur	Flexible (Yearly/Hourly)	Hourly	Europe (ENTSO-E Member States)	User-defined (from coarse to fine-grained); 220-750 kV grid	Generation capacity, transmission capacity, line utilization, costs	Open-source, uses OpenStreetMap data, frequently updated, validated against ENTSO-E data
Kijak and Gashi, 2024	Strategic BESS Lifecycle Planning	Long-term (full life cycle)	Not explicitly defined	Global	Not specified	Safety, reliability, compliance with IEC standards, asset management (ISO 55001)	Focuses on integrating international standards for long-term reliability and minimizing operational risks.
Biancardi et al., 2024	EuroMod	2030 projection	Not explicitly defined	Europe	Cross-border interconnectors	Transmission surplus, financial viability of interconnectors, impact of BESS deployment	Evaluates how BESS competes with transmission infrastructure, emphasizing the need for integrated planning in Europe.

each criterion.

1. Open-Source
Open-source availability ensures transparency, adaptability, and reproducibility, making it a fundamental requirement for this research. Stakeholders emphasized the importance of collaborative tools (Market Interview 1), particularly for integrating diverse inputs such as land costs and zoning constraints. An open-source model allows policymakers and grid operators to validate and reproduce results, fostering trust and ensuring that model insights can be adapted to evolving regulatory conditions.

2. Adaptability
Adaptability ensures that the model can simulate a variety of scenarios, reflecting the evolving dynamics of energy systems and addressing insights from interviews and literature. For example, Chapter 2 identified uncertainty in zoning policies and grid priorities (TenneT interview 1) as key barriers to BESS deployment. An adaptable model enables scenario analysis to explore how varying these factors impacts BESS placement. Additionally, adaptability supports exploring the future implications of increasing renewable energy penetration and land-use competition (SQ2). This flexibility allows the research to generate robust conclusions across different time horizons (2023 and 2040) and spatial configurations.

3. Energy System Planning Analysis
The ability to analyze interactions between storage, generation, demand, and transmission is key to addressing the main research question. Chapter 2 highlighted the operational concerns of grid stability, congestion management, and peak load reduction. This criterion ensures the model captures these technical dimensions, enabling realistic assessments of BESS placement. Literature, such as Schmidt and Staffell (2023), also underscores the need to link financial trade-offs (e.g., land costs) with technical metrics, such as average line loading. The model's capacity to perform system-wide planning bridges

these technical and economic aspects.

4. Spatial Resolution
Spatial resolution is important for incorporating localized factors, such as land availability, exclusion zones, and proximity to substations, identified as critical in Chapter 2. The interviews revealed that market participants prioritize locations near HV substations (market interview 1), to minimize cable costs, while spatial constraints like Natura 2000 zones further limit feasible sites (TenneT interview 3). Literature, including N. Wang et al. (2020), emphasizes the importance of detailed spatial granularity for realistic modeling of land-use trade-offs. This criterion supports answering SQ2 by enabling an evaluation of how spatial restrictions influence BESS placement. Provincial reports like those by Repowered and APPM (2023) or CE Delft and NP RES (2022) estimate a capacity density between 100 MWh and 140 MWh per ha for BESS. This indicates that a fine granularity is required for a proper spatial requirement assessment.

5. Data Requirements
Balancing data accessibility and accuracy ensures that the model can integrate publicly available datasets (e.g., Copernicus EU (2020) and "Open Street Map" (n.d.)) while using additional data from TenneT and other sources. Aside from enhancing the research's efficiency, data availability was identified in chapter 2 as a challenge for some regions (Interview 3) alongside the reliance on aggregated information for neighboring countries. A model with manageable data requirements ensures consistent outputs while addressing these gaps. This criterion directly supports SQ3 by allowing the integration of region-specific cost data and exclusion criteria, enabling a realistic assessment of economic and spatial impacts on BESS deployment.

6. Documentation and Community Support
Documentation and an active user community provide essential support for troubleshooting and extending the model's functionality. The iterative modeling process relies on feedback loops between simulation results and stakeholder insights. An active community ensures the model remains robust and adaptable as new data or policy constraints emerge. Moreover, well-documented models facilitate alignment with policymakers, aiding in the translation of optimization results into actionable recommendations.

Table 3.2: Criteria Description

Criteria	**Description**
Open-source	Ensures transparency, accessibility, and the ability to modify the model for specific needs.
Adaptability	Supports different scenarios, time scales, and configurations, allowing flexibility in analysis.
Energy system planning analysis	Enables optimization and evaluation of energy systems, including integration of BESS.
Spatial Resolution	Captures regional variations to identify optimal BESS placement based on local factors.
Data requirements	Balances accuracy with the use of publicly available or easily accessible data.
Documentation and Community Support	Provides clear guidance and a collaborative community for troubleshooting and enhancements.

3.1.3. Model suitability analysis

PyPSA-Eur stands out as the most suitable modeling framework for this research based on its performance across key evaluation criteria depicted in table 3.3. All considered models are fully open-source, enabling custom modifications essential for incorporating spatial constraints and addressing research-specific needs. In terms of adaptability, Calliope excels due to its flexibility in modeling multi-sector energy systems and its ability to simulate spatial and temporal variations. Although PyPSA-Eur is slightly harder to navigate, it still offers strong adaptability, particularly in grid-specific analyses, which aligns with the focus of this study. GRIM scores lower due to its narrower focus on renewable investment and customization would require in-depth knowledge of energy system modeling.

When it comes to energy system planning, PyPSA-Eur is the most comprehensive, effectively integrating generation, storage, and transmission. This capability directly supports the research's need to assess system-wide impacts of BESS placement, such as grid congestion and system costs. Calliope provides robust planning tools but lacks the same level of specialization in grid-level analyses (in its base form), while the focus of GRIM on renewable investments makes it less applicable for storage-specific evaluations. All three models handle spatial resolution well, offering fine granularity to integrate geographic and land-use constraints, such as exclusion zones and proximity to substations.

Table 3.3: Comparison of Spatially Explicit Models

Criteria	GRIM	PyPSA-Eur	Calliope
Open-Source	++	++	++
Adaptability	+	+	++
Energy system planning analysis	+-	++	+
Spatial Resolution	++	++	++
Data Requirements	-	+	-
Documentation and Community Support	- -	++	+

In terms of data requirements, PyPSA-Eur achieves a balance by utilizing publicly available datasets, such as OpenStreetMap, transmission line data, CORINE Land Cover, and ENTSO-E generation data, alongside proprietary inputs from TenneT, ensuring the research can incorporate both open and project-specific data. GRIM and Calliope, can incorporate the same information, but are not equipped with it in its original form.

Finally, PyPSA-Eur outperforms the other models in documentation and community support. It offers detailed documentation, an active GitHub repository with around 380 stars, and a robust academic and industry community, ensuring ease of implementation and troubleshooting (Hörsch et al., 2018). Calliope provides good documentation and an active user base but has a smaller community compared to PyPSA-Eur. GRIM, however, lacks substantial documentation and community support, further limiting its practicality.

In conclusion, PyPSA-Eur is considered the optimal choice for this research. Its strengths in open-source accessibility, suitability for large networks, detailed energy system planning, and robust community support make it well-suited for addressing the research questions. While Calliope offers notable adaptability and spatial resolution, its lower computational efficiency and narrower focus make it less suitable for grid-specific studies. GRIM's limited accessibility, narrower scope, and lack of community support further reinforce PyPSA-Eur as the best modeling framework for optimizing BESS placement within the Dutch HV grid.

3.2. Model Conceptualization

The conceptualization phase forms the foundation of the modeling methodology by identifying the critical components, relationships, and constraints of the Dutch energy system relevant to optimal BESS placement. This process is informed by the PyPSA-Eur base model, insights from the academic literature study, and interviews with industry experts.

PyPSA-Eur (Python for Power System Analysis – Europe) is an open-source, power system model that provides a robust framework for analyzing European energy systems. It is particularly suited for scenarios that require the integration of spatial, temporal, and technical data, making it a critical tool in this research's focus on spatially explicit BESS optimization.

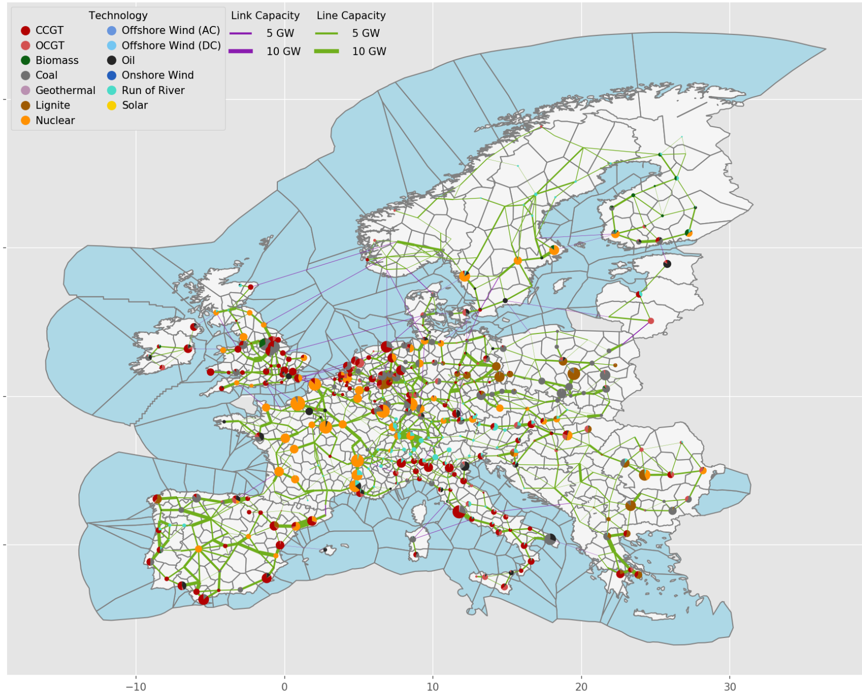


Figure 3.1: PyPSA-Eur network clustered to 512 nodes (Hörsch et al., 2018)

3.2.1. Model Overview

PyPSA-Eur is designed for modeling the 220 kV to 700 kV high-voltage power transmission network across ENTSO-E member states, using nodes (buses) and edges (transmission lines and transformers) to represent the system. The network is spatially structured through Voronoi tessellation, which allocates demand and generation to specific nodes, dividing the grid into distinct service areas. Illustratively, figure 3.1 displays the whole network clustered to 512 nodes. Each bus serves as a generator, load (demand), or slack/reference bus that balances the system. Connections between buses include AC power lines and transformers, which account for physical energy flow constraints.

To maintain computational efficiency while preserving spatial and system accuracy, the original PyPSA-Eur network—typically modeled with 200–300 nodes requiring 100–150 GB RAM for optimization—is clustered down to 37 nodes, allowing simulations to be solved within 4 hours using 16GB RAM and the licensed Gurobi solver. This clustering balances model complexity with feasibility while ensuring that key cross-border electricity flows are retained.

The model enforces energy and charge conservation laws using the bus admittance matrix and power flow equations, ensuring consistency across operational states. It primarily relies on linearized optimal power flow (LOPF) for optimization-based analyses, meaning it models real power (P), voltage amplitude (|V|), and phase angle (θ) but does not explicitly capture reactive power (Q) and voltage stability effects. While nonlinear AC power flow is supported, LOPF, DC-OPF, and lossless formulations (LF) omit voltage dependencies, limiting detailed AC grid dynamics representation.

This research applies PyPSA-Eur to a 37-node clustered network, prioritizing the Dutch electricity system while incorporating neighboring countries to capture key cross-border interactions. Figure 4.1 visualizes this network in a nodal power network map. Chapter 4 further details the network topology and spatial modeling adjustments made for this study.

3.2.2. Key Features and Capabilities

The objective is to model the spatial and economic impacts of BESS deployment within the high-voltage grid (220–380 kV) using the PyPSA-Eur framework by Hörsch et al. (2018). Key elements of the model include:

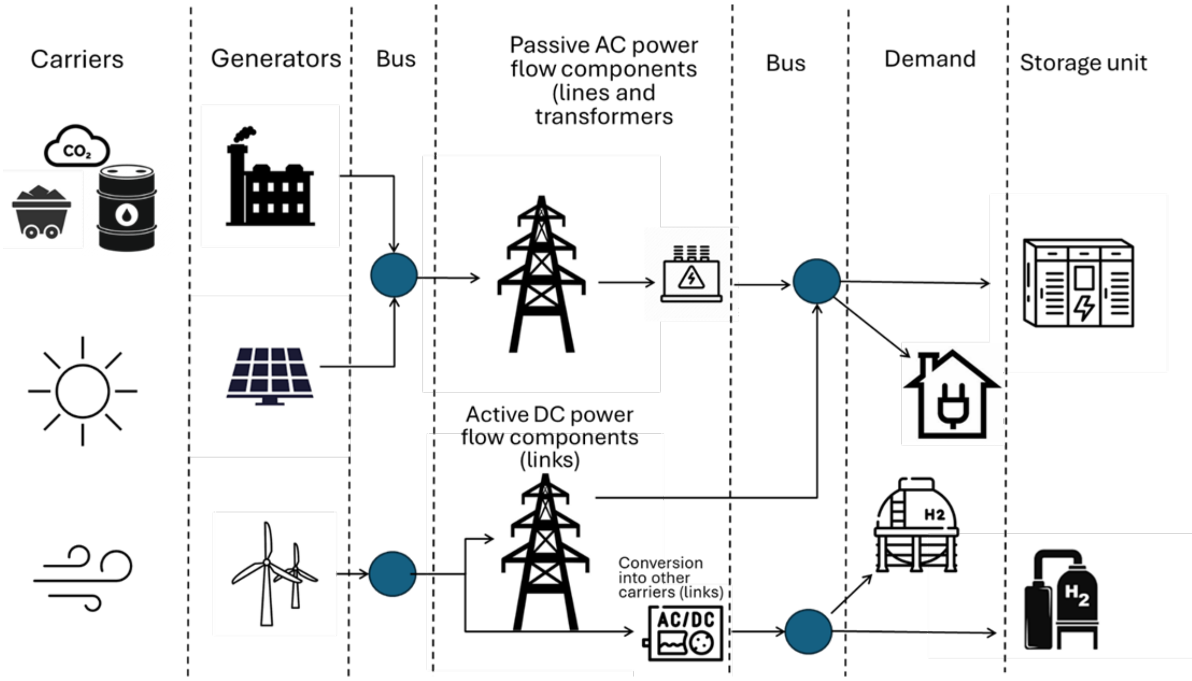


Figure 3.2: Simplified overview of PyPSA-Eur functionality

System Components:

- **Nodes (Buses):** Represent high-voltage substations and key energy transfer points in the network. These serve as connection points for generators, storage units, loads, and transmission infrastructure.
- **Edges (Lines):** Represent AC transmission lines that connect nodes within a region or country. They are constrained by thermal limits (maximum allowable current) and the maximum installable capacities, which govern the amount of power that can flow through the network. Lines model the internal grid and are crucial for balancing supply and demand locally.
- **Links:** Represent high-capacity interconnectors, typically for DC transmission, connecting different regions or countries. Links are designed to facilitate cross-border energy exchange and are optimized separately from internal transmission lines.
- **Generators:** Include renewable energy sources (e.g., solar, wind) and conventional sources (e.g., gas, coal). Their operation is constrained by capacity factors, representing resource availability, and marginal costs.
- **Storage Units:** Model energy storage technologies such as batteries. They are treated as nodes with specific power and energy capacities, governed by operational constraints, including state of charge (SOC), round-trip efficiency, and energy storage limits.

A simplified overview of this is given in figure 3.2.

System Boundaries:

- **Geographical Scope:** The model spans the Netherlands (18 nodes) and neighboring countries (Norway, Belgium, Denmark, Germany, the UK, and Ireland) aggregated into 19 nodes to capture cross-border interactions (specified weightings can be found in table 4.1.
- **Temporal Resolution:** Simulates a full year with hourly time steps (8760 hours) to capture intra-day variability.
- **Spatial Resolution:** Based on NUTS-3 regions for the Netherlands and broader aggregation for neighboring countries. Land availability is based on the CORINE land cover database considering Europe in rasters of 1 ha.

Modeling Objectives:

- **Cost Optimization:** Minimizing system-wide costs while ensuring technical feasibility.
- **Carbon Constraints:** Evaluating the system under decarbonization targets aligned with Dutch climate goals.
- **Spatial Feasibility:** Incorporating land-use constraints, exclusion zones, and land costs.

The model assumes that energy demand remains inelastic, and the optimization framework prioritizes supply-demand balancing at each node. PyPSA-Eur focuses on power system optimization by building on widely used Python libraries such as Pandas and Numpy. It offers scalable computational capabilities, enabling high-resolution temporal (hourly) and spatial simulations. While sector coupling is possible, this thesis employs the model in its electricity-only configuration to prioritize the specific challenges associated with large-scale BESS deployment in the electricity grid. Spatial constraints are incorporated using geographic data from "Open Street Map" (n.d.) and land-use restrictions from the Corine Land Cover (CLC) dataset (Copernicus EU, 2020). These datasets allow the model to account for exclusion zones such as NATURA2000 conservation areas, ensuring realistic deployment scenarios. The model integrates technology and cost data from the Danish Energy Agency, providing standardized parameters for system components, including batteries, wind turbines, and solar panels. These parameters ensure consistency with state-of-the-art energy cost projections.

An important note is that PyPSA-Eur adopts a normative rather than descriptive modeling framework. As such, the results are optimal solutions that align with specified constraints, but they may not directly mirror real-world outcomes due to practical implementation barriers. Moreover, incomes are not explicitly modeled in PyPSA-Eur since the optimization increases generation-, storage-, and transmission capacities until the break-even point (which is determined by the interest rate). Chapter 6 reflects further on the implications of these points.

3.2.3. Geographic Granularity

Defining an appropriate geographic granularity is essential to balancing computational efficiency and spatial accuracy in the optimization model. The model prioritizes high-resolution representation of the Netherlands, and includes neighboring countries in lower resolutions to account for cross-border electricity flows without excessive computational overhead. The grid is clustered into Voronoi-based service areas, assigning each node to its nearest geographic center, effectively determining the spatial allocation of generation, demand, and storage assets. This ensures that BESS placement reflects realistic technical and land-use constraints while maintaining model efficiency.

Spatial constraints are incorporated using the CLC dataset, which provides 100m x 100m resolution land-use classifications to exclude protected areas, urban zones, and other unsuitable locations from BESS deployment (Copernicus EU, 2020). In PyPSA-Eur, spatial restrictions are applied via an availability matrix based on CLC codes, allowing technology-specific exclusion areas (see appendix C for detailed descriptions). However, a key limitation exists: BESS is not modeled as a separate spatial entity but is attached to buses, which act as aggregated demand and supply points without explicit geographic coordinates. Since buses are not spatially constrained by the CLC exclusions, a direct availability matrix for BESS cannot be generated. To address this, the solar PV availability matrix is used as a proxy to determine spatial feasibility for BESS deployment, ensuring land-use constraints are indirectly accounted for in site selection. Section 4.1.3 further details how node-specific exclusions are implemented in the case study.

By integrating land-use constraints through the CLC dataset and adapting the availability matrix, this approach ensures that BESS placement aligns with real-world spatial limitations while maintaining computational efficiency. Despite PyPSA-Eur's limitations regarding explicit bus-level exclusions, this methodology ensures that BESS siting decisions reflect both technical feasibility and regulatory restrictions in a spatially constrained energy system.

3.3. Model Formalization

The formalization phase involves mathematically representing the electricity system within the PyPSA-Eur framework to define a computationally solvable optimization problem. This problem focuses on determining the cost-optimal placement and capacity of large-scale BESS in the high-voltage grid, accounting for constraints such as grid topology, renewable energy profiles, demand patterns, exclusion zones, and land costs. By formalizing these elements into objective functions and constraints, the model quantifies agent behavior, decision-making rules, and system dynamics.

The process begins with describing data inputs and the model's data collection methodology. Subsequently, the optimization problem and constraints are formulated to identify cost-optimal configurations of the network under increasing renewable energy integration. The objective is to minimize total system costs while ensuring operational feasibility, reliability, and adherence to de-carbonization targets. This is achieved using the PyPSA-Eur model, which incorporates considerations of generation, storage, transmission, demand, and system flexibility.

3.3.1. Model data collection

The initial phase involves gathering data on energy generation patterns, demand distribution, and system parameters like: land use, spatial regulations, financial considerations, and land prices. Although some data already exists in the PyPSA database, missing data was sourced internally from TenneT and from the literature. Cleaning and refining the raw data is crucial to address errors, missing values, and inconsistencies before constructing the energy system model. For each data type, a concise explanation is provided, outlining its definition and the acquisition method.

Electricity Generation and Demand

PyPSA-Eur regionalizes electricity demand by distributing a country's total demand across its regions using a weighted factor. This factor is composed of 60% regional GDP and 40% regional population (Hörsch et al., 2018).

Generation capacities can be used from a database already included in the base version of the model, but can also be served to the model as user input data. Furthermore, these variables can be made non-extendable to prevent them from changing as a result of the optimization. This allows for the analysis of the system under predefined generation capacities.

For the 2023 scenario, historic demand and- generation data was used and is further detailed in appendix C. Generation capacity was fixed and set to non-extendable to ensure that each scenario is based on the same data to provide a common starting point.

For 2040, future demand and generation capacities were derived primarily from TenneT projections and supplemented with optimization results for certain components. More specifically, renewable capacity data including solar-PV, offshore wind, onshore wind, and nuclear was sourced from TenneT. The other indicators (gas, coal, oil, and biomass) were optimized first in a separate base simulation where these indicators were made extendable. This choice is justified since these values were more ambiguous in TenneT reports for which the optimization would yield a fitting total generation capacity in accordance to demand. The resulting optimized generation capacities were then fixed for future simulations to ensure each simulation has a common starting point (see appendix C). Specific numerical values are detailed in Chapter 4

Assessing BESS Location Suitability

The next step is identifying the most suitable locations for installing BESS within the defined geographical regions. This assessment focuses on land-use compatibility. The Dutch regions are represented as nodes in the model. OpenStreetMap project "Open Street Map" (n.d.) can be used as a basis for performing a land cover assessment. This assessment identifies the degree of exclusion for all parts of land (no-go zone, partial exclusion, etc.). Utilizing data such as the CLC database, areas are evaluated based on their proximity to the electricity grid's high voltage stations, population density, and environmental constraints. To narrow down the possible locations, exclusion criteria such as protected natural reserves or densely populated urban areas are applied. These zones are deemed unsuitable for BESS installation due to ecological or social concerns.

Since the CLC database only contains historical land availability data, both simulations are based on the land availability of the latest dataset (2018). This means that the 2040 simulation does not account for the likely significant changes in the Dutch land availability for BESS over time.

Cost Parameters

Financial data related to BESS installation costs, operational expenses, and projected return on investment will utilize the cost data already incorporated within the PyPSA framework. PyPSA's integrated database includes standardized cost assumptions for various energy technologies, including Li-ion batteries and other storage systems, based on reputable sources such as the International Energy Agency (IEA) and market intelligence reports. This approach ensures consistency and aligns with the model's broader design while avoiding the need for additional data collection.

An important element to note, is that PyPSA-Eur only models (BESS) incomes based on the day-ahead market (DAM). A significant 37,6% of BESS income can be attributed to ancillary services which are hence not included (TenneT, 2024a). Therefore, the CAPEX of BESS is reduced accordingly before the optimization to take into account this income handicap. In a system with an increasing amount of BESS capacity, this income from ancillary services is expected to decrease, until nearly all income comes from the DAM. Therefore, the named handicap is not considered in the 2040 simulations

In PyPSA, the capital cost attribute represents the annualized investment cost, facilitating the distribution of upfront expenses over the asset's lifetime. While the total CAPEX remains fixed, its annualized representation should be adjusted to align with the specific duration of your simulation to ensure accurate cost assessment. More details about the integration of BESS in the PyPSA-Eur workflow are discussed in chapter 4.

3.3.2. Objective Function

The objective function minimizes the total annual system costs, including capital investments, operational costs, and grid expansion expenditures:

$$\min_{x} C_{\text{total}} = \sum_{t \in T} \left(C_{\text{gen},t} + C_{\text{storage},t} + C_{\text{transmission},t} \right), \tag{3.1}$$

where:

- $C_{\text{gen},t}$: Cost of electricity generation, including fuel and variable O&M costs,
- $C_{\text{storage},t}$: Cost associated with energy storage, such as charging, discharging, and efficiency losses,
- $C_{\text{transmission},t}$: Costs related to transmission line utilization, network expansions, and maintenance.

Investment costs for new assets are annualized using an annuity factor to account for capital recovery over their lifetime. Grid expansion, an endogenous flexibility mechanism in PyPSA, includes both capital and operational expenditures for new and existing infrastructure. While expansions are a capital investment, ongoing O&M costs impact total system expenditures, especially when BESS deployment reduces the need for grid reinforcements. Including these costs provides a comprehensive assessment of trade-offs between infrastructure investments and operational efficiency, though grid expansion remains a secondary focus in this study.

The a (annuity factor) is given by:

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

where r is the discount rate and n is the asset lifetime in years. This ensures that CAPEX costs are distributed over the operational lifespan of BESS, generators, and grid components.

3.3.3. Constraints

The optimization problem is subject to a set of equality and inequality constraints that ensure the feasibility and efficiency of the power system. These constraints are categorized into power balance, transmission, generation, storage, and global constraints. Each is detailed below.

Power Balance: At every node and timestep, electricity supply must balance demand, accounting for generation, storage operations, and imports/exports through transmission. This is expressed as:

$$\sum_{g\in G} P_{g,t} + \sum_{s\in S}\left(P^{\text{ch}}_{s,t} - P^{\text{dis}}_{s,t}\right) - \sum_{l\in L} P_{l,t} = D_t, \quad \forall t \in T.$$

Here, $P_{g,t}$ represents power generated by generators, $P^{\text{ch}}_{s,t}$ and $P^{\text{dis}}_{s,t}$ are storage charging and discharging powers, $P_{l,t}$ is transmission power flow, and D_t is demand.

Transmission Constraints: Transmission line power flows are limited by their thermal capacities and expansion constraints. The absolute flow of power must satisfy:

$$|P_{l,t}| \leq P^{\text{max}}_l, \quad \forall l \in L,\, t \in T.$$

Additionally, transmission line capacities can be expanded within predefined upper limits $\bar{P}_l$:

$$0 \leq P^{\text{max}}_l \leq \bar{P}_l, \quad \forall l \in L.$$

where $\bar{P}_l$ is the upper expansion limit for each line. This accounts for grid reinforcements required to handle system congestion.

Generation Constraints: Generators must operate within their nominal capacities and are constrained by resource availability for renewables. The dispatch is bounded as follows:

$$0 \leq P_{g,t} \leq P^{\text{max}}_g, \quad \forall g \in G,\, t \in T.$$

For variable renewable generators, P^{max}_g depends on capacity factors derived from weather data.

Storage Dynamics and Constraints: Storage components' state of charge (SoC) evolves based on charging and discharging operations. This is governed by:

$$E_{s,t} = E_{s,t-1} + \eta^{\text{ch}}_s P^{\text{ch}}_{s,t} - \frac{P^{\text{dis}}_{s,t}}{\eta^{\text{dis}}_s}, \quad \forall s \in S,\, t \in T.$$

The SoC must remain within storage capacity limits:

$$0 \leq E_{s,t} \leq E^{\text{max}}_s, \quad \forall s \in S,\, t \in T.$$

Storage energy capacity is proportional to power capacity, scaled by the maximum discharge time h^{max}_s:

$$E^{\text{max}}_s = h^{\text{max}}_s \cdot P^{\text{max}}_s.$$

Global Constraints: To achieve decarbonization and renewable integration goals, global constraints limit CO_2 emissions and enforce renewable energy shares. Carbon emissions are calculated as:

$$\sum_{g\in G} \frac{P_{g,t} \cdot e_g}{\eta_g} \leq \text{CAPCO}_2, \quad \forall t \in T,$$

where e_g is the emission factor and η_g is efficiency. Renewable energy targets are enforced as:

$$\sum_{g\in G^{\text{renewable}}} P_{g,t} \geq \alpha D_t, \quad \forall t \in T,$$

where α represents the desired renewable share.

3.4. Model Implementation & -Usage

3.4.1. Implementation

The implementation phase involves applying the formalized model to assess its functionality and performance. During this phase, the model is executed under different scenarios to analyze how various variables interact and impact the outcomes. This process facilitates the exploration of diverse designs and operational configurations for optimal BESS allocation. Three scenarios were tested across two temporal networks (2023 and 2040) and are represented in overview table 4.2.

3.4.2. Scenarios

This study adopts three scenarios: BASE, COL, and EXCL. Firstly, the BASE scenario describes the network in which no spatial- or financial restrictions are imposed. It is meant to provide a benchmark- and referentially optimal configuration. To this end, model parameters relating to generation and demand are fixed for each scenario to isolate the effect of each specific scenario constraint. Specific generation modeling parameters are listed in appendix C.

Costs of Land

To account for the costs of land at each node, it is important to consider the investment characteristics inherent to land. Namely, while BESS loses its value after its lifetime (which is 25 years in this research), land does not depreciate. Therefore, instead of incorporating its specific investment costs per hectare (ha), the opportunity costs are included here. Opportunity costs represent the potential benefits or returns lost when choosing one alternative over another, such as the income foregone by using land for a battery instead of investing its value elsewhere. These costs are assumed to be 8% in this case and were coordinated with TenneT.

Notably, PyPSA assumes capital cost as an annualized investment. This characteristic should be taken into account when calculating the cost of land for each bus. The following calculation was made to model the cost of land for BESS:

The *annualized land cost per MW* is based on the total land cost, spread over the economic lifetime of the battery using the annuity factor:

$$\text{Annualized Land Cost (€/MW)} = \text{Land Cost (€/MW)} \times a$$

where a (annuity factor) is:

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

with:

$$r = 0.08 \quad \text{(8\% annual opportunity cost rate)}$$
$$n = 25 \quad \text{(battery lifetime in years).}$$

The COL scenario incorporates regional land costs into the optimization model via an addition to the annualized CAPEX of BESS to evaluate their influence on BESS placement decisions. Since land availability is a critical constraint in infrastructure planning, including land prices in the cost function provides a more realistic assessment of spatial-economic trade-offs. Given the lack of project-specific land cost data, this study assumes that BESS is sited exclusively on farmland, using provincial farmland prices as a regional cost indicator. This assumption allows for a structured analysis of how land prices impact total system costs and the geographic distribution of BESS deployment.

Exclusion of Land

PyPSA can assess the spatial availability of land through the creation of an availability matrix, which is based on a combination of technology-specific characteristics (such as energy density per ha), and land type suitability. Land type suitability is based on the CLC database and can be manually adjusted within the model (summarized in C.9).

Since batteries are directly linked to nodes in PyPSA-Eur (unlike generation units such as solar-PV and wind), no availability matrix can be created for them. To overcome this barrier, the availability matrix of solar-PV is used to analyze exclusion areas surrounding buses. Respondent 5 [interview 5] implicated that BESS developers are not inclined to place BESS outside a 2 km radius of a station. Therefore, if no available land lies within 2 km, BESS capacity is set to 0 for that node. A drawback to this approach is that nodes in this study do not represent real-world station coordinates, for which the exclusion is not based on the actual availability of suitable land surrounding stations. While reducing real-world applicability, this method does expose the effects of exclusion areas for BESS on overall system performance for which it is still highly relevant to this study.

3.4.3. Usage

The usage phase focuses on interpreting and analyzing the model outputs, ensuring that the optimization results provide actionable insights into BESS placement, system flexibility, and grid performance. This phase ensures that the results are contextualized, robust, and applicable to varying scenarios.

The primary goal is to translate the model's technical outputs into meaningful conclusions for grid planning and policy development. This involves:

1. **Scenario-Based Interpretation & Post-Processing**

   Results from the BASE, COL, and EXCL scenarios are compared to assess the impact of land-use constraints and economic factors on BESS deployment. The differences in BESS placement, grid congestion, and system costs are analyzed to determine which spatial and economic conditions drive key trade-offs. Moreover, the 2040 projections are compared to 2023 baseline results to evaluate how increasing renewable penetration and electrification affect system flexibility needs.

   Subsequently, key metrics such as line loading, line expansions, and BESS capacities are extracted to assess system performance under each scenario.

2. **Reliability & Sensitivity Analysis**

   Although a global sensitivity analysis—which systematically explores the impact of all input variations—would provide the most comprehensive insight, time constraints and deep uncertainties inherent to energy system modeling justify a one-time sensitivity analysis for this research. Given the complexity of long-term projections, factors such as policy changes, technological advancements, and market dynamics introduce uncertainties that cannot be fully captured within a single model framework.

   To assess the robustness of the optimization approach, a targeted sensitivity analysis is conducted by adjusting key input parameters, specifically land costs and exclusion constraints. By varying these parameters, the study evaluates how spatial and economic uncertainties affect BESS placement, total system costs, and reliance on grid expansion. Finally, aggregated BESS capacity outputs are compared with the II3050 scenario data, ensuring that results remain within realistic operational limits. This approach ensures that while the model remains computationally feasible, it still provides valuable insights into the stability of the results under alternative conditions.

By systematically analyzing and refining the outputs, this phase ensures that the model's conclusions are practically relevant for system operators and policymakers. Figure 3.3 provides a summary of the modeling strategy employed in this study. It visualizes the model flow including input data, constraints, model outputs, and post-processing results.

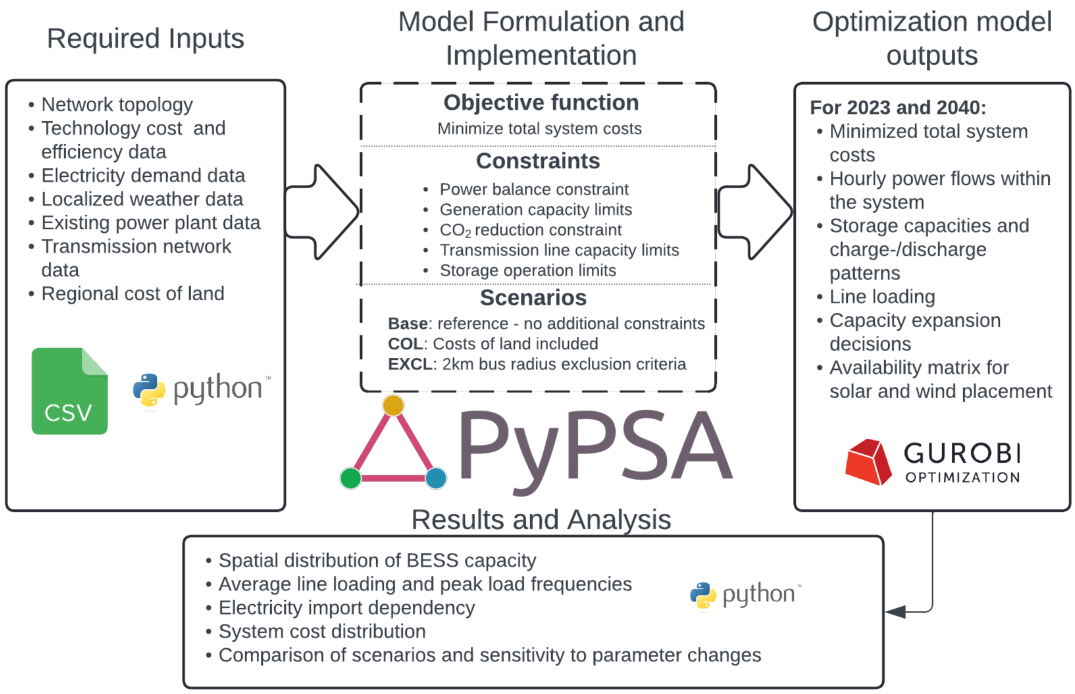


Figure 3.3: Model flow overview

3.5. Conclusion

This chapter outlined the methodological framework used to analyze the spatial and economic constraints influencing the placement of BESS in the Dutch HV electricity grid. Through a structured model selection process, PyPSA-Eur was identified as the most suitable tool due to its ability to integrate technical, economic, and spatial constraints while maintaining computational efficiency. Compared to other power system models such as Calliope and GRIM, PyPSA-Eur's large amount of included open-source databases, and flexibility in incorporating network topology, land-use constraints, and energy system planning requirements makes it particularly well-suited for this research.

The model conceptualization phase described the key functionalities of PyPSA-Eur, including its representation of generation, storage, and transmission infrastructure using a nodal clustering approach. Special attention was given to the spatial resolution of the model, which ensures a fine granularity for the Netherlands while incorporating cross-border interactions through coarser resolution clusters in neighboring countries. A notable limitation of PyPSA-Eur is its inability to directly model BESS as spatially independent assets; instead, storage is linked to substations, requiring the use of a proxy method (solar-PV availability matrices) to impose land-use restrictions.

In the formalization phase, the optimization objective was established to minimize total system costs, balancing BESS deployment with grid expansion while ensuring operational feasibility. The key constraints included power balance equations, network flow limitations, and economic feasibility conditions. The model differentiates between fixed parameters (such as demand projections and generation capacities) and decision variables (BESS placement and grid expansion investments), ensuring a structured optimization process.

Implementation focused on defining the case study's two temporal snapshots (2023 and 2040) and three scenarios (BASE, COL, and EXCL), which assess the effects of land costs and exclusion zones on BESS siting. The chosen scenarios directly stem from insights gained in Chapter 2, ensuring consistency between the theoretical framework and the model application.

Deep uncertainties in future energy system evolution limit the extent to which long-term results can be fully validated. To account for these uncertainties, a sensitivity analysis was incorporated to test the robustness of key assumptions, including land cost variations.

This chapter laid the foundation for the case study, which is presented in Chapter 4. There, the model is applied to quantify how spatial and economic constraints affect BESS placement, system congestion, and total network costs. The upcoming analysis will provide empirical insights into the trade-offs between battery deployment and grid expansion, ultimately informing strategic planning for energy storage in the Dutch HV grid.

4

Case Study

Understanding the spatial and economic constraints that influence BESS placement requires the application of an optimization model tailored to real-world conditions. This chapter presents the case study that applies the PyPSA-Eur model to the Dutch high-voltage grid to analyze how spatial exclusions and economic land-use considerations affect BESS deployment. The objective is to translate the theoretical model developed in Chapter 3 into a scenario-based simulation that reflects the Dutch electricity system.

To achieve that, next, Section 4.1 outlines the network and the different simulations and scenarios evaluated in this study. Following this, Section 4.2 details the model parameters and assumptions, covering key inputs such as electricity demand, renewable generation profiles, land-use constraints, and financial parameters. These inputs form the foundation for the optimization model and directly influence the placement and operation of BESS within the Dutch energy system.

To ensure the reliability of the model outcomes, Section 4.3 presents a validation analysis, assessing how well the model aligns with real-world feasibility. This section also discusses the methodological constraints that should be considered when interpreting the results.

Finally, Section 4.4 summarizes the key conclusions of this chapter, linking the case study findings to the broader research objectives of this thesis. The results presented here provide quantitative insights into the trade-offs between spatial constraints, economic feasibility, and grid integration, serving as a foundation for the analysis and interpretation in Chapter 5.

4.1. Network Overview and Simulations

4.1.1. System Network

The Dutch HV grid is the base for this model. To balance computational labor and system accuracy, the grid network is clustered into 37 nodes. Neighboring countries of the Netherlands have also been included to account for import- and export electricity flows.

Figure 4.1 (Nodal Map) visualizes the network and its primary components, with the focus weight percentages for each country displayed in table 4.1. The focus weights represent the proportion of clusters allocated to each country during the network clustering process. This is a critical step in ensuring that the resulting network topology accurately reflects the European power grid's complexity and interconnectedness. By assigning 50% of the focus weight to the Netherlands, this study prioritizes high spatial and temporal resolution in the Dutch grid, aligning with the research's primary objectives. However, to preserve the integrity of the model and maintain realistic cross-border electricity flows, weights are also distributed to neighboring countries. For example, Great Britain (20%) and Norway (5%) are explicitly weighted to prevent their isolation in the clustering process, which could lead to unrealistic results.

The ability to assign focus weights is a powerful feature in PyPSA-Eur that allows researchers to control the granularity of clusters across regions. This flexibility is particularly valuable when certain countries,

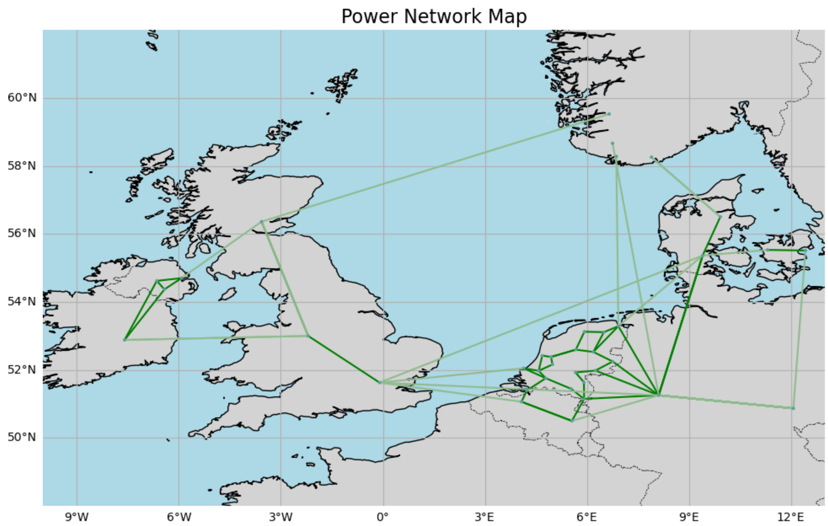


Figure 4.1: Power network map (37 clusters)

like the Netherlands in this case, require more detailed modeling due to their strategic importance in the study.

Table 4.1: Focus Weights by Country

Country	Focus Weight (%)
Germany (DE)	6%
Ireland (IE)	4%
Great Britain (GB)	20%
Denmark (DK)	10%
Norway (NO)	5%
Belgium (BE)	5%
Netherlands (NL)	50%

The bus numbering map (Figure 4.2) provides an additional visualization of how nodes are structured within the Netherlands, allowing for the interpretation of model results in later chapters.

To maintain spatial consistency in the grid representation, Voronoi tessellation is used to assign each grid node to its nearest geographic center, effectively dividing the network into distinct service areas. Figure 4.3 illustrates system-wide Voronoi cells (left) and Dutch-specific Voronoi cells (right), showing how the clustering approach maintains a balanced spatial distribution while preserving the connectivity of transmission assets.

The clustered network serves as the foundation for the simulations and scenarios analyzed in this study. The next section outlines the temporal snapshots and scenario framework, detailing how different spatial and economic constraints influence BESS deployment strategies.

4.1.2. Simulation Timeframes

In consultation with TenneT, the decision was made to create two networks with temporal perspectives of 2023 and 2040 respectively. The 2023 network would describe status-quo optimal BESS configurations based on historical data. The 2040 network would show the situation as a result of predicted future demand, emission goals, and the penetration of renewable electricity generation. It should be noted that this future scenario is subject to a high degree of inherent uncertainty for which assumptions had to be made (highlighted in Section 4.2). Each temporal network is divided into three scenarios as described in Chapter 3 (3.4.1).

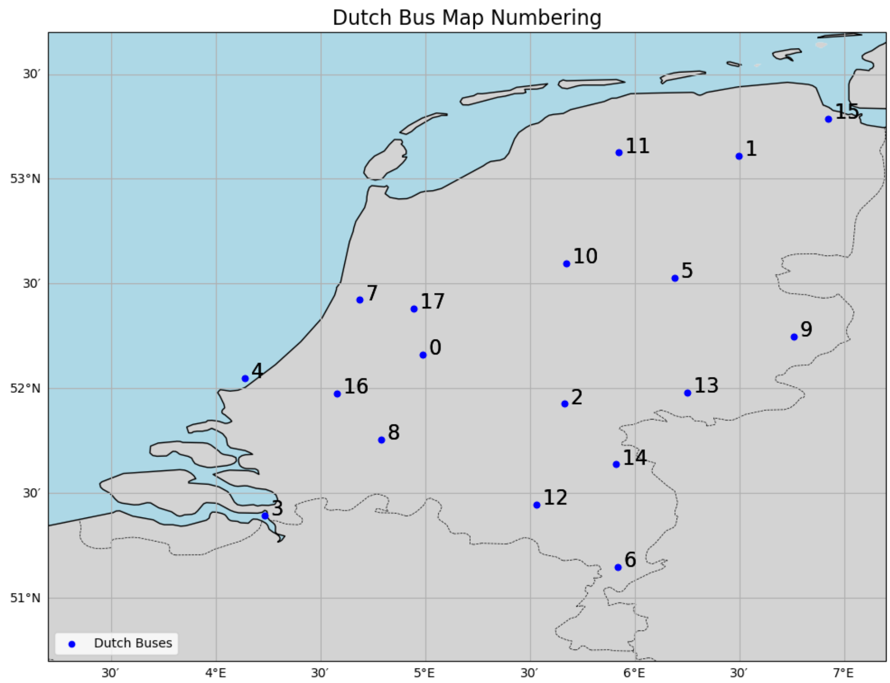


Figure 4.2: Dutch system with bus numbering

4.1.3. Simulation Scenarios

This study considers three scenarios to vary the degree of financial- and spatial restrictions for BESS allocation in the Dutch HV grid. Table 4.2 summarizes the key differences.

Table 4.2: Scenario Configurations

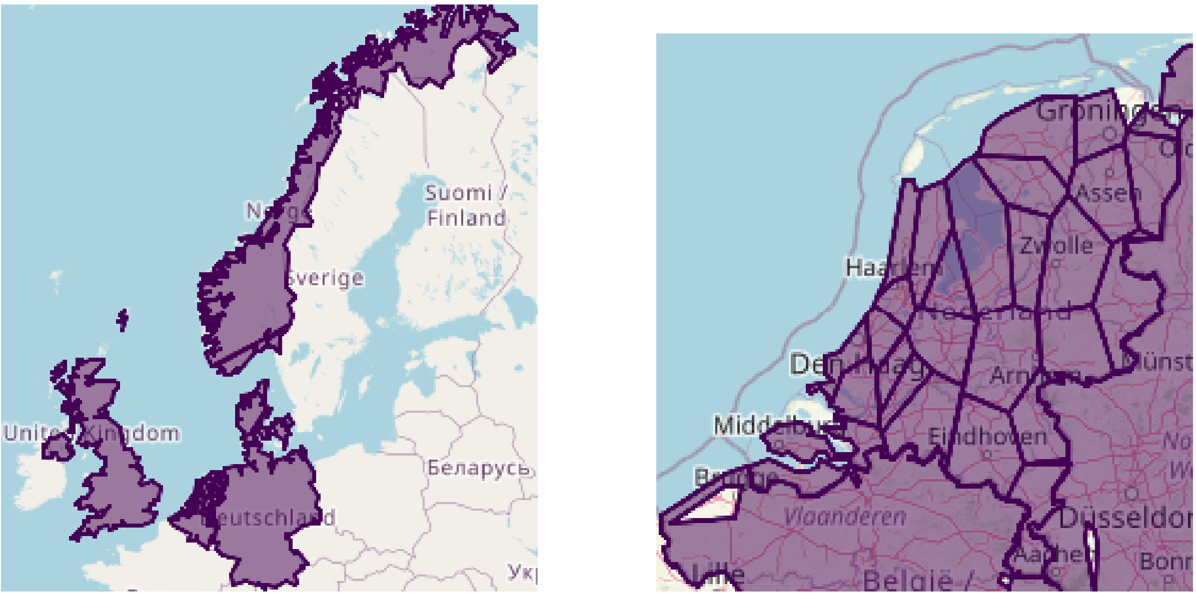
Scenario	Cost of Land	Exclusion Zones	Description
BASE	Not included	None	Benchmark scenario without spatial or economic constraints
COL	Included (€/m²)	None	Reflects regional land cost variations
EXCL	Included (€/m²)	2 km radius	Limits BESS placement to near-substations

Costs of Land (COL)

To evaluate the impact of regional land costs on BESS deployment, the COL scenario applies provincial farmland prices as a cost parameter in the model. While actual land prices vary significantly per project, as confirmed in TenneT Interview 3, using farmland prices provides a structured basis for regional cost differentiation. Table 4.3 presents the land cost data used for this analysis. These costs are integrated into the optimization framework to examine whether higher land prices shift BESS placement and influence total system costs.

Exclusion of Land (EXCL)

Since Batteries are directly linked to nodes in PyPSA-Eur, no availability matrix can be created for them. Therefore the availability matrix of solar-PV is used to analyze exclusion areas surrounding buses. Respondent 5 [interview 5] implicated that BESS developers are not inclined to place BESS outside a 2 km radius of a station. If no available land lies within 2 km, BESS capacity is set to 0 for that node. Table 4.4 indicates which buses are excluded as a result of the 2 km exclusion criteria. Notably, only six nodes were found to be eligible for BESS placement under the named restrictions, for which this scenario represents a major exclusion of (12) possible allocation options.



(a) System Voronoi Cells

(b) Dutch Voronoi Cells

Figure 4.3: Voronoi Cells: System-wide and Dutch-specific.

Table 4.3: Cost of Land per Province

Province	COL [€/ha] (Kadaster, 2024)	MWh/ha	Hours BESS	COL [€/MW]	COL [€/MWh]
Noord-Holland	€78,500.00	100	6	€4,710.00	€785.00
Zuid-Holland	€80,800.00	100	6	€4,848.00	€808.00
Flevoland	€182,700.00	100	6	€10,962.00	€1,827.00
Overijsel	€74,600.00	100	6	€4,476.00	€746.00
Noord-Brabant	€90,400.00	100	6	€5,424.00	€904.00
Groningen	€70,500.00	100	6	€4,230.00	€705.00
Friesland	€60,800.00	100	6	€3,648.00	€608.00
Drenthe	€76,300.00	100	6	€4,578.00	€763.00
Gelderland	€77,800.00	100	6	€4,668.00	€778.00
Zeeland	€78,000.00	100	6	€4,680.00	€780.00
Limburg	€86,100.00	100	6	€5,166.00	€861.00
Utrecht	€79,300.00	100	6	€4,758.00	€793.00

The specific land types or infrastructures that are excluded are taken from PyPSA-Eur's base configuration and CORINE land cover data set and are listed in Table C.9 of Appendix C(Copernicus EU, 2020).

4.2. Model Parameters & Assumptions

This section details the key model parameters and assumptions underlying the optimization framework, including energy generation patterns, electricity demand, spatial constraints, and financial considerations. While some datasets are directly available in PyPSA-Eur, additional data was sourced from TenneT, literature, and official reports. To ensure consistency, all inputs underwent cleaning and preprocessing before integration into the model.

Although a comprehensive parameter overview is provided in Table C.1 (Appendix C), this section highlights the most relevant parameters for interpreting the results presented in the next chapter.

4.2.1. Demand Data

For the 2023 scenario, historical demand and generation data have been used (see Appendix C). The demand data for 2023 is directly sourced from PyPSA-Eur's base input datasets. Specifically, the total

Table 4.4: Bus Eligibility Status for the EXCL scenario

Bus	P_nom_max
NL0 0	Included
NL0 1	Included
NL0 2	Excluded
NL0 3	Excluded
NL0 4	Excluded
NL0 5	Excluded
NL0 6	Excluded
NL0 7	Included
NL0 8	Included
NL0 9	Included
NL0 10	Included
NL0 11	Excluded
NL0 12	Excluded
NL0 13	Excluded
NL0 14	Excluded
NL0 15	Excluded
NL0 16	Excluded
NL0 17	Excluded

electricity demand for the Netherlands in 2023 is 110 TWh.

As mentioned, PyPSA-Eur regionalizes this electricity demand by distributing a country's total demand across its regions using a weighted factor. This factor is composed of 60% regional GDP and 40% regional population (Hörsch et al., 2018).

To project electricity demand for future years, PyPSA-Eur applies a scaling factor that adjusts demand relative to the base year input data. For the 2040 scenario, the II3050 National Leadership (NAT) scenario has been selected, which estimates a total electricity demand of 327 TWh for the Netherlands (Netbeheer Nederland, 2023). This scenario was chosen in collaboration with TenneT, as it is considered the most relevant due to its high level of electrification, leading to a greater dependence on the electricity infrastructure.

While the demand projections for other countries may follow different scaling factors, the Dutch electricity demand can be approximated using a scaling factor of 3, calculated as follows:

327TWh/110TWh = 3

Since the main focus of this research is on the Dutch network, this factor was employed for demand predictions.

4.2.2. Generation Data

Generation data was fixed in the model to ensure each simulation had a common starting point. For 2023, historical data was retrieved from various sources as can be seen in table 4.5.

For the 2040 scenario, renewable electricity generation data was sourced from the ENTSO-E Pan-European Market Modeling Database (PEMMDB). However, there were two key challenges in directly using this data:

1. **Classification Complexity:** Non-renewable generation data in PEMMDB was often fragmented into multiple sub-categories, making it difficult to accurately aggregate this information for each country.
2. **Mismatch with the II3050 (NAT) Scenario:** The total generation capacity from PEMMDB does not necessarily align with the assumptions of the II3050 National Leadership (NAT) scenario. This could lead to discrepancies between projected electricity demand and available generation capacity.

Table 4.5: Installed generation capacity per technology in GW for base year 2023

Carrier	BE[1]	DE[2]	DK[1]	GB[3]	NL[1]	NO[4]	IE[5]
Nuclear	3.908	0.000	0.000	5.883	**0.482**	0.000	0.000
Offshore Wind	2.263	8.500	2.343	14.741	**5.269**	0.096	0.200
Onshore Wind	2.500	58.000	6.100	14.000	**4.500**	5.073	4.100
Gas (CCGT and OCGT)	6.000	29.600	1.500	30.000	**20.000**	0.000	4.652
Coal (incl. Lignite)	1.800	36.800	1.000	1.000	**3.500**	0.000	0.855
Oil	1.000	0.000	0.500	0.500	**0.500**	0.000	0.292
Solar-PV	5.000	66.000	2.500	14.000	**15.000**	0.299	0.720
Hydro	0.000	0.000	0.000	0.000	**0.000**	34.139	0.000
Biomass	0.800	9.000	1.000	3.000	**2.000**	0.642	0.042

[1] IRENA (n.d.), [2] Burger (2024), [3] Department for Energy Security and Net Zero (DESNZ (2023), [4] Energy Facts Norway (2024), [5] EirGrid and SONI (2024) and SEAI (2024).

To address these issues, the renewable generation capacities from PEMMDB were fixed, ensuring consistency with the provided data. Meanwhile, non-renewable generation capacities were made extendable, meaning they were left flexible and subject to optimization within the model. After running test simulations, the optimized non-renewable capacity values were then assumed and fixed for the final simulations. A summary of the final generation capacity values per country for the 2040 simulations is provided in Table 4.6.

Table 4.6: Installed generation capacity per technology in MW for 2040

Carrier	BE	DE	DK	GB	**NL**	NO	IE
Nuclear [1]	0.000	0.000	0.000	13.236	**1.500**	0.000	0.000
Offshore Wind [1]	6.560	64.723	10.722	95.158	**41.500**	2.000	11.096
Onshore Wind [1]	18.412	158.878	4.925	42.040	**15.100**	2.475	9.686
Gas	18.412	244.256	1.500	61.131	**11.734**	0.000	4.398
Coal	0.000	40.791	1.000	5.834	**6.901**	0.000	1.096
Oil	0.127	0.786	0.000	0.000	**0.000**	0.000	0.208
Solar-PV [1]	26.285	365.875	36.419	59.287	**122.700**	2.500	13.162
hydro	0.000	0.000	0.000	0.000	**0.000**	37.400	0.000
Biomass	6.251	8.012	21.644	3.000	**0.220**	0.642	0.068

[1] *TenneT PEMMDB dataset 2040, personal communication (2024)*

Operational Expenses

For the 2023 scenario, two test simulations were performed with lower marginal generation costs for coal, gas, and oil, corresponding to CO_2 prices of €100/tonne and €200/tonne, respectively (Table 4.7). In both cases, no batteries were allocated in the network. Therefore, the decision was made to use the highest marginal generation costs, corresponding to a CO_2 price of €400/tonne for 2023, as this resulted in greater deployment of variable renewable generation, necessitating increased system flexibility. This aspect will be further explored in the discussion chapter.

Table 4.7: Marginal Costs of Generation Sources at Different CO_2 Prices

Generation source	**MC(CO_2 - 100) €/MWh**	**MC 2023 (CO_2- 200) €/MWh**	**MC(CO_2 - 400) €/MWh**
Natural Gas	€ 84,66	€ 118,30	**€ 185,59**
Coal	€ 128,55	€ 229,06	**€ 430,08**
Oil	€ 202,90	€ 285,72	**€ 451,36**

4.3. Validation

Ensuring the reliability of model outputs is crucial for drawing meaningful conclusions on BESS placement and system-wide effects. This study employs three key validation methods: using the transparency of PyPSA-Eur, comparing results with TenneT's II3050 NAT scenario, and incorporating expert discussions with TenneT. Each of these methods helps to assess the robustness and relevance of the model assumptions and results.

As an open-source model, PyPSA-Eur benefits from continuous peer review and empirical validation, ensuring that its power flow calculations, capacity expansion constraints, and network optimization methods are widely accepted. The model's datasets, including ENTSO-E demand profiles, SARAH3-ERA5 weather data, and high-voltage infrastructure parameters, further reinforce the accuracy of 2023 baseline simulations. These data sources ensure that the model closely reflects real-world grid operations and demand patterns, supporting the reliability of the base-year analysis.

For future projections, full empirical validation is inherently impossible due to uncertainties in demand growth, policy developments, and technological advancements. This study aligns with TenneT's II3050 NAT scenario, which represents a high-electrification pathway requiring significant grid adaptation (Netbeheer Nederland, 2023). A direct comparison shows that the 2040 large-scale BESS capacity projection (24.3 GW) from the II3050 NAT estimates align closely to the modeling outcomes, confirming that the scenario assumptions are consistent with Dutch energy transition planning. While this provides confidence in the 2040 scenario, it is important to interpret future-year results as exploratory rather than predictive, given that policy changes, economic shifts, and unforeseen technological developments could alter real-world deployment patterns.

Additionally, discussions with TenneT experts helped refine the network representation, spatial constraints, and economic assumptions, ensuring alignment with real-world grid planning considerations. This iterative approach between modeling and expert review strengthens the practical relevance of the study's findings. However, it should be noted that while 2023 simulations are empirically grounded, and 2040 projections align with recognized planning scenarios, the absence of transition modeling limits insights into intermediate system developments.

To address the lack of temporal data for 2040, this research employs a "snapshot optimization strategy," using 2023 weather and demand profiles scaled for 2040 loads. This means that the analysis is focused on an end-state system configuration rather than modeling the transition pathway to that state. While this approach allows for computational feasibility within the study's scope, it does not capture dynamic interactions such as phased grid expansion, evolving market conditions, or investment decision-making over time. Future research could improve upon this by integrating time-dependent modeling approaches to assess investment sequencing and transition dynamics.

PyPSA-Eur provides a simplified methodology for estimating future energy demands. By default, demand is distributed based on a weighted sum of GDP (60%) and population (40%) for each region. This assumption oversimplifies actual demand patterns, as local energy consumption may be influenced by industrial activity, electrification rates, and socio-economic factors that are not captured in this distribution. For the purpose of this study, and in consultation with TenneT, numbers from the National Leadership scenario in the Netbeheer Nederland (2023) report were used to refine the 2040 demand projections. Future studies could enhance demand estimation by incorporating regionalized electrification rates, sector-specific energy growth models, and spatially explicit demand forecasting.

A further modeling limitation relates to the use of Voronoi cells in PyPSA-Eur to allocate load and generator data to transmission network substations. While this approach maintains spatial consistency at a high level, it does not account for the topology of the underlying high-voltage stations. As a result, assets may be incorrectly assigned to substations, leading to potential inaccuracies in local congestion estimation. Future work could address this by integrating distribution network modeling alongside HV grid simulations to refine spatial placement accuracy.

By leveraging an established open-source model, validating against national energy scenarios, and incorporating expert input, this study ensures that its findings are methodologically robust and practically relevant. Nonetheless, future research should build on these validations by improving spatial granularity, dynamic system evolution modeling, and integration of real-world market mechanisms, ensuring continued accuracy and applicability of storage deployment planning.

4.4. Conclusion Chapter 4

This chapter outlined the case study for applying the PyPSA-Eur model to evaluate constraints affecting BESS placement. The network overview established the spatial structure of the model, clustering the grid into 37 nodes to balance computational feasibility and geographic granularity. The inclusion of neighboring countries ensures realistic cross-border electricity trade, preserving the integrity of system-wide interactions. Using Voronoi tessellation, the clustering process ensures an accurate representation of generation and demand distribution, while prioritizing detailed resolution within the Netherlands.

The simulations were designed to capture both short-term and long-term system conditions. The study evaluated BESS deployment across two temporal perspectives—2023 and 2040—each subdivided into three scenarios (BASE, COL, and EXCL). These scenarios assess the impact of land costs and spatial exclusions on BESS allocation, providing a structured analysis of how economic and geographical constraints influence system-wide outcomes.

Key modeling parameters were systematically defined, integrating datasets from PyPSA-Eur, TenneT, and official Dutch energy reports. While the model inherently validates itself through its open-source structure, further validation was achieved through alignment with TenneT's II3050 NAT scenario, which forecasts a 327 TWh demand and a 24.3 GW large-scale BESS capacity requirement by 2040.

Overall, this chapter provides the foundation for interpreting the optimization results in Chapter 5. The structured scenario analysis enables a quantitative assessment of BESS placement strategies, offering insights into the trade-offs between land-use constraints, economic feasibility, and grid integration. The findings will serve as a basis for discussing the implications of spatially constrained BESS deployment and its role in achieving the Netherlands' energy transition goals.

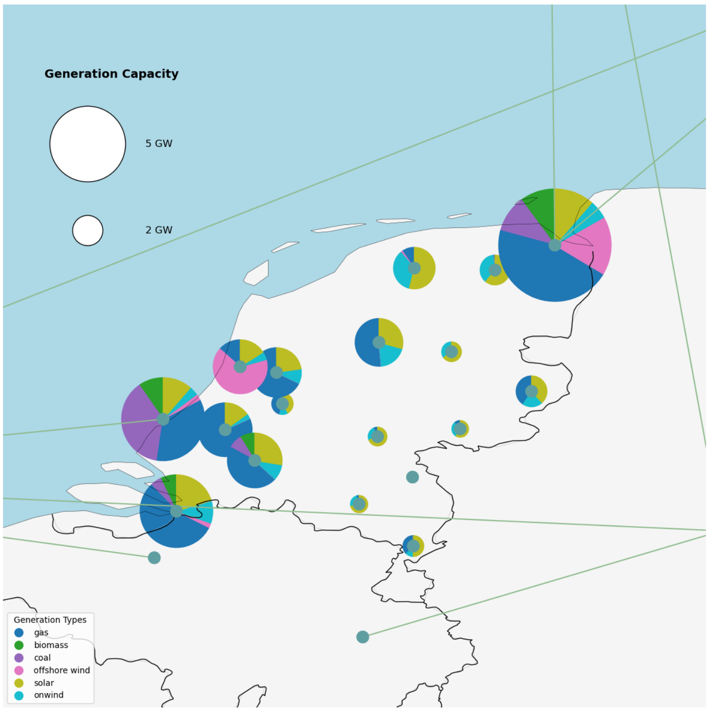
5 Optimization Model Results

In this chapter, the results of the optimization model are presented. Due to the abundance of different outputs, a selection is made to include only those results considered relevant for answering the research questions. The model that was created aims to identify the optimal BESS capacities at each node within the representation of the Netherlands in 2023 and 2040. The purpose is then to see how these values vary under changing conditions. As discussed in the methods section, a total of 6 network variations were created, three for each test year. For each year there is one base network simulation, which is not restricted in terms of BESS allocation. The second network is created with location-specific cost of land included and is named *COL scenario*. The third network also uses these land costs, but also includes an exclusion criteria dictating BESS can only be placed if sufficient space is available within a 2 km radius from the bus. This network is referred to as the *EXCL scenario*.

This chapter is structured as follows: First, the results of the optimization model for the 2023 simulations are discussed in Section 5.1, focusing on the spatial distribution of BESS capacity, net congestion, line utilization and expansions, electricity import and export, and system investment costs. These analyses address sub-questions 2 and 3, which explore the impacts of competing land use, exclusion areas, and land costs. Following this, the simulations for 2040 are examined in a similar way in section 5.2 in which an additional line expansion analysis is shown. Finally, section 5.3 concludes this chapter by listing the most relevant results which shall be discussed further in chapter 6.

5.1. Simulation Results 2023 Scenario

Each scenario is based on the same data and network structure to ensure a common starting point. Therefore, the Dutch 2023 network including regionalized generation capacity is first presented in figure 5.1. The size of each pie chart represents the generation capacity aggregated to that node. The pie chart further indicates what the relative distribution of this generation capacity is per technology. As before, OCGT and CCGT are grouped together, as are coal and lignite-based generation. Overall, a high degree of gas generation can be seen throughout the country indicated by the dark blue color in the pie charts. Furthermore, generation capacity appears to be higher around the most populated cities in the south-western parts of the country, and in the top north. Furthermore these locations coincide with the industrial clusters of the Netherlands identified in the Nationaal Programma Verduurzaming Industrie (NPVI) (n.d.).



* Nodes size proportionally to their respective generation capacities with higher capacities shown as larger nodes

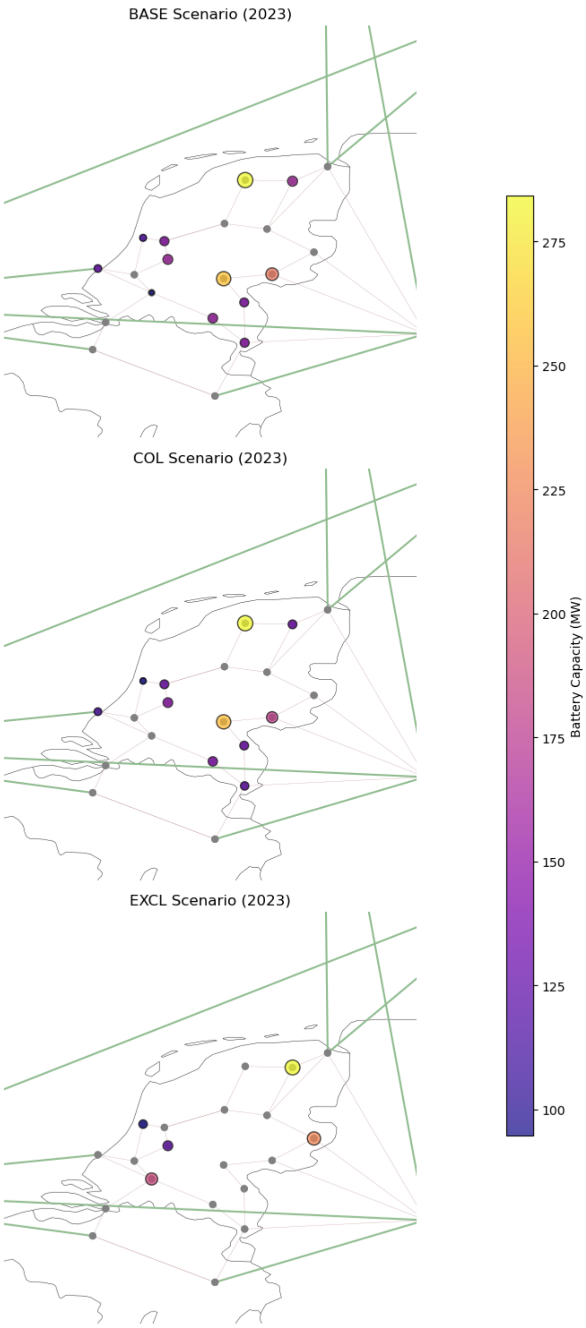
Figure 5.1: Overview of the 2023 network

5.1.1. Spatial distribution of BESS capacity 2023

The placement of BESS in the network is determined by both technical and economic constraints embedded in the model. Figure 5.2 illustrates the optimal spatial distribution of BESS capacity in the Netherlands for each of the three 2023 simulation scenarios. The color scale on the right indicates the relative capacity of each BESS installation, with larger yellow markers representing higher capacities and grey markers indicating buses with no allocated BESS. The BESS configurations presented in this subsection serve as the foundation for the subsequent analysis of their effects on congestion, line utilization, import/export dynamics, and system costs.

The results indicate that BESS is predominantly allocated to nodes with a high share of renewable generation. For instance, Bus NL11 in the central north, which relies primarily on solar and onshore wind power (as shown in Figure 5.1 with yellow and light blue), receives the highest BESS capacity. In contrast, nodes with significant fossil-based generation, such as gas or coal plants, tend to have lower BESS allocations likely due to their capability to dispatch flexibly in response to real-time demand. Despite these variations, BESS capacity is generally distributed across the country in both the BASE and COL scenarios. The EXCL scenario, which restricts BESS placement to only six nodes, naturally exhibits a more concentrated deployment, with moderate capacity increases at certain nodes that received little or no BESS in the BASE scenario.

To quantify the effects of spatial and economic constraints on BESS deployment, Table 5.1 presents the precise capacity allocation for each node across the three 2023 scenarios, along with the relative changes compared to the BASE scenario.



** Nodes size proportionally to their respective capacities with higher capacities shown as larger nodes*

Figure 5.2: BESS capacity-location map 2023

The inclusion of land costs in the COL scenario has a minimal impact on BESS allocation, leading to only a 9% reduction in total installed capacity. However, in the EXCL scenario, spatial constraints significantly alter the distribution and total capacity of BESS. Due to the exclusion criteria (i.e., lack of available land within a 2 km radius of a bus, as detailed in Table 4.4), BESS placement is heavily restricted, forcing the model to concentrate storage capacity at a limited number of eligible nodes. Despite this restriction, the model does not compensate by significantly increasing BESS capacities at the permitted locations, but by increasing system reliance on flexible generation capacity (discussed furher in Section 5.1.4). As a result, the total BESS capacity in the EXCL scenario is 43% lower than in the BASE scenario.

Finally, Table D.1 summarizes the spatial requirements for each BESS installation in hectares. In the BASE scenario, a total land area of nearly one km² is required for BESS deployment across the Dutch grid.

Before drawing conclusions about the role of BESS in the system, it is essential to assess its system-wide impacts under these different spatial and economic conditions. The following subsections will analyze how each scenario influences grid performance, congestion management, and overall system efficiency to provide a more comprehensive understanding of the trade-offs associated with spatial constraints.

Table 5.1: Optimal BESS Capacity Data (MW) and Percentage Delta from Base (2023)

Bus	Base [MW]	COL [MW] (% change)	EXCL [MW] (% change)
NL0 0	124	120 (-3.2%)	124 (-0.0%)
NL0 1	128	99 (-22.7%)	284 (+121.9%)
NL0 2	263	262 (-0.4%)	0 (-100.0%)
NL0 3	0	0 (0.0%)	0 (0.0%)
NL0 4	75	77 (+2.7%)	0 (-100.0%)
NL0 5	0	0 (0.0%)	0 (0.0%)
NL0 6	104	91 (-12.5%)	0 (-100.0%)
NL0 7	63	50 (-20.6%)	95 (+50.8%)
NL0 8	31	0 (-100.0%)	188 (+506.5%)
NL0 9	0	0 (0.0%)	226 (+100.0%)
NL0 10	0	0 (0.0%)	0 (0.0%)
NL0 11	301	301 (0.0%)	0 (-100.0%)
NL0 12	118	112 (-5.1%)	0 (-100.0%)
NL0 13	204	162 (-20.6%)	0 (-100.0%)
NL0 14	101	99 (-2.0%)	0 (-100.0%)
NL0 15	0	0 (0.0%)	0 (0.0%)
NL0 16	0	0 (0.0%)	0 (0.0%)
NL0 17	106	100 (-5.7%)	0 (-100.0%)
Total	**1,618**	**1,474 (-8.9%)**	**917 (-43.3%)**

5.1.2. Congestion and Line Utilization 2023

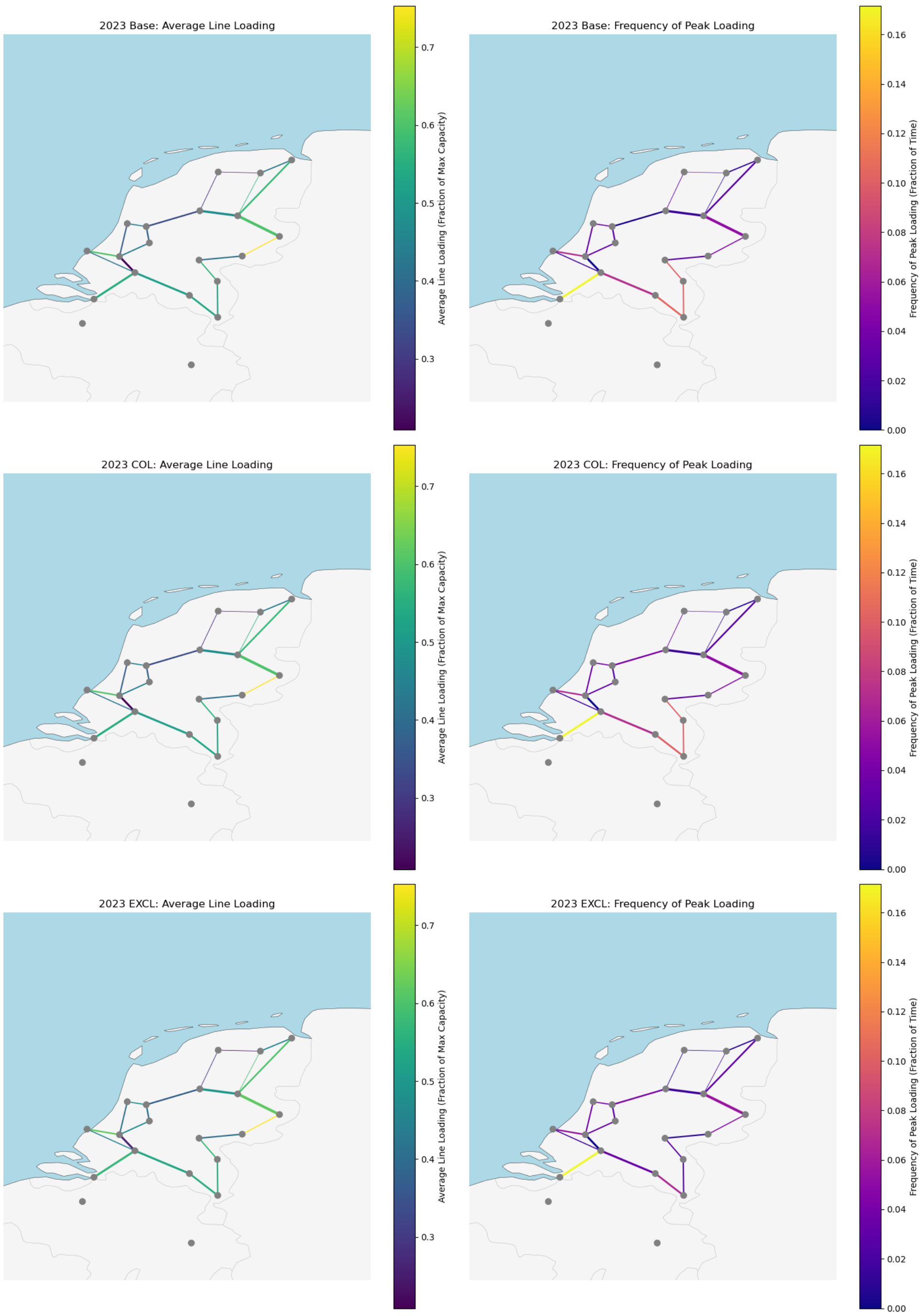
Based on the three BESS configurations outlined above, an analysis was performed to identify how each of these scenarios impacts net congestion and line utilization. Accordingly, figure 5.3 presents two sub-graphs that illustrate line loading and peak load frequency across the three scenarios in 2023. The left sub-graph visualizes average line loading as a fraction of its maximum capacity. The color gradient (from blue to yellow) hence indicates how much of the maximum line capacity is utilized across the year, on average. The thickness of the lines represents the absolute transport capacity, regardless of how much it is being used. The right sub-graph then shows the frequency of peak loading, indicating how long each line operates at its maximum capacity during the year. An important note is that, while both graphs display yellow as the highest value, their scaling is independent. While the left graph highlights overall network efficiency (relevant for long-term planning), the right graph can aid in identifying moments of stress that require grid expansion or -upgrading to prevent outages. Numeric values underlying the figure can be found in table D.3 of the appendix.

The BASE scenario shows a relatively uniform distribution of the average line loading across the network. Most lines operate at moderate capacities between 40% - 60% of their maximum. Some transmission lines closer to the northeast show slightly higher average utilization displayed by slightly lighter green and yellow line colors. Furthermore, the right graph shows that southern parts of the country experience more frequent peak loadings, indicated by orange and yellow line colors. Notably, the line with the highest average line loading does not have a high peak frequency indicating a stable high load.

For the COL scenario, there is a slight increase in the frequency of peak loading in the central part of the country. However, it remains largely equal to the BASE scenario. This indicates that the minor redistribution of BESS in the COL scenario has no significant impact on line loading and peak load frequency.

The EXCL scenario results in a network that has a similar average line loading distribution as the other networks. Moreover, the lines in the south-eastern parts of the country show a lower peak frequency than in the other networks represented by slightly more purple lines. These results indicate that major restrictions on BESS allocation options (resulting in a lower total installed capacity) do not directly impact congestion and line loading. Nevertheless, since other flexibility means are balanced in the optimization, these outcomes do not directly indicate the significance of BESS in the system. The following subsections illustrate that other flexibility means (such as cross-country connections, or using more flexible generation options) provide more cost-efficient alternatives than putting more stress on the grid or placing more BESS on eligible nodes in these configurations.

A further analysis was performed to analyze the impact of N-1 principles by imposing a 90% line capacity limit. It shows that under these constraints, line peak capacity is reached significantly more often with some lines being used at peak capacity 40% of the time. This analysis is detailed in Appendix D.



** Line thickness represents line capacity while its color indicates average line loading (left) or peak load frequency (right)*
*** Note that the color scale values are different between the left and right graphs*

Figure 5.3: Congestion and line loading 2023

5.1.3. Line Expansion and Import/Export Balance 2023

Line Expansion

Due to the minimal impact of different BESS configurations on congestion and line loading, an additional analysis was conducted to examine line expansions and import/export balances. Table 5.2 summarizes the AC- and DC grid expansions compared to the BASE scenario. For clarity, only values > 50 MW have been included. Notably, the COL scenario shows limited variation from the BASE scenario with regard to line capacities. For the EXCL scenario some AC expansions can be seen up to 195 MW with no observed significant DC expansions.

These observations indicate that the reduced installed BESS capacity in the EXCL scenario urges investments in AC grid expansions to compensate sub-optimal system configuration. The quantification of these investments is outlined in the next section.

Table 5.2: Filtered Grid Expansion Comparison (Δ > 50 MW) 2023

Bus 0	Bus 1	Line Type	Type (COL)	Net COL [MW]	Type (EXCL)	Net EXCL [MW]
NL0 1	NL0 11	AC	Expansion	2	Expansion	180
NL0 1	NL0 15	AC	Expansion	3	Expansion	74
NL0 10	NL0 11	AC	Expansion	1	Expansion	67
BE0 1	NL0 6	AC	Expansion	6	Expansion	101
NL0 10	NL0 5	AC	Expansion	17	Expansion	50
NL0 12	NL0 8	AC	Expansion	2	Expansion	79
NL0 13	NL0 2	AC	Expansion	9	Expansion	195
NL0 14	NL0 2	AC	Expansion	5	Expansion	81
NL0 14	NL0 6	AC	Expansion	4	Expansion	109
NL0 3	NL0 8	AC	Expansion	13	Expansion	71
TOTAL				**66**		**969**

Import and Export

Another potential effect of the different BESS configurations is a change in how much energy should be imported or exported by the Netherlands. Given that the Netherlands is highly interconnected with neighboring electricity markets, BESS placement could influence cross-border electricity flows.

For the 2023 simulations, the results show negligible differences in terms of import/export dependencies between scenarios. Although this does not provide per-hour insights, the overall annual capacity exchanges do not change significantly. The BASE scenario and the COL scenario yield nearly equal results. The EXCL scenario shows a slightly decreased need for electricity imports in the Netherlands and Belgium from the UK (0.32 TWh and 0.23 TWh respectively). Table D.5 summarizes all net import/export balances between countries in a comparable overview, but it is not shown here for readability purposes.

5.1.4. System Costs 2023

To assess the broader economic implications of these scenarios, the annualized system costs related to BESS investments, AC transmission line capacity, HVDC and converter capacity, and variable operating costs are evaluated associated with different scenarios for BESS placement. This helps to determine whether spatial or financial constraints impose significant trade-offs on overall system efficiency.

The costs of the system are identified by calculating the objective function of the optimization model. However, since much of this objective value represents sunk costs (such as fixed generation costs), this number is not considered relevant for this analysis. Rather, the sum of costs that vary per scenario are taken into account: Battery investment costs, HVDC-, converter-, and AC transmission line CAPEX. The sum of these components shows insignificant differences across scenarios in 2023, as can be seen in table 5.3.

Figure 5.4 displays for each scenario how much each of these individual system components differ from the base model value. Each bar represents the difference in a specific cost category relative to the BASE scenario. Positive values represent an addition to the system cost component, while negative values represent a reduction compared to the BASE scenario. The final bar sums up these deltas to present the total cost changes in each scenario.

Battery investment costs represent the total capital investment required for battery storage units. It is calculated as the product of the optimized battery capacities and their capital costs. It shows reductions in both scenarios: In the COL scenario, there is a modest decrease of €1.9M, reflecting slightly fewer investments in battery capacity compared to the BASE scenario. The EXCL scenario shows a much larger reduction of €10.8M, driven by stricter exclusion constraints limiting battery installation.

These reductions in battery costs, however, result in compensatory cost increases in other areas, particularly variable operating costs. These costs represent the operational expenses of electricity generation (such as CO_2 costs and fuel costs), calculated as the product of generator dispatch and their marginal costs. For the COL scenario, these costs increase by €1.8M, while for the EXCL scenario, the increase is much more substantial at €9.1M.

This reflects a higher dependency on dispatchable generators to maintain system reliability when battery installations are reduced. Furthermore, it indicates that, in an optimal configuration where BESS location options are limited, increased usage of existing electricity generation plants allows for a near-cost-optimal alternative under the studied circumstances.

HVDC and converter costs are slightly higher in both scenarios and represent the capital costs of HVDC lines and converters (links), calculated as the product of optimal link capacities and their capacity costs. The COL scenario experiences an increase of €0.1M, while the EXCL scenario sees an increase of €1.3M. This indicates that reduced battery capacity leads to mildly higher reliance on cross-country grid connections in the system, increasing overall system operating expenses. AC line capital costs, representing investments in transmission lines, see small increases in both scenarios. The COL scenario adds €0.3M, while the EXCL scenario incurs a slightly higher increase of €2.7M, suggesting that grid reinforcements are required to compensate for limited battery deployment.

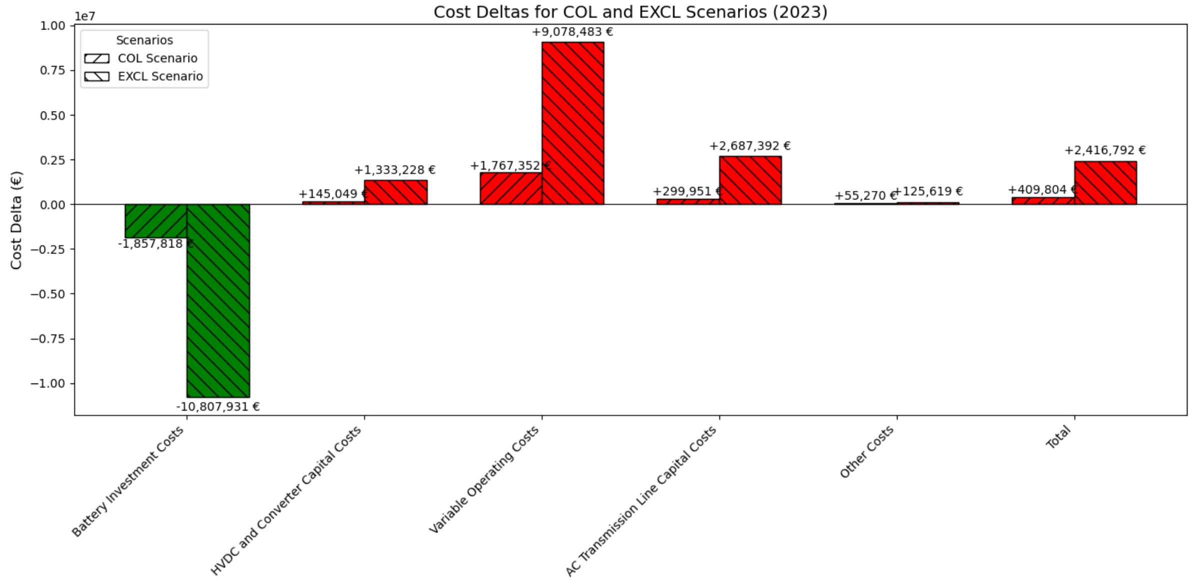
The other costs category includes residual elements not directly captured in the other categories. Both scenarios show small increases in this category, with the COL scenario at €55k and the EXCL scenario at €0.1M. These residual changes likely arise from modeling artifacts or unclassified costs and merit further exploration to identify their origins.

The total cost deltas highlight the overall system cost changes. In the COL scenario, there is a net increase of €0.4M, indicating relatively minor system-wide cost impacts due to marginal reductions in battery investments. However, the EXCL scenario shows a larger total cost increase of €2.4M, emphasizing the greater financial burden imposed by strict exclusion criteria. This increase however, is no significant change compared to the €8.1B summed system investment costs, as shown in Table 5.3. It also shows that both scenarios require less investments in links (HVDC and converter elements), AC transmission lines, and BESS than the BASE scenario. The explanation for this can be found in the waterfall diagram which shows that the variable operating costs are the main driver of total cost increase.

Table 5.3: Simulation Results for 2023 Scenarios

Simulation	**BASE**	**COL**	**EXCL**
Total System Costs	€ 59.2B	€ 59.2B	€ 59.2B
Delta (compared to base)	–	€ 0.4M	€ 2.4M
Investments in links, lines, and BESS	€ 8.1B	€ 8.1B	€ 8.1B
Delta (compared to base)	–	- € 1.4M	- € 6.8M

** Displayed costs represent annualized investment costs as discussed in Section 3.3.1 ** Include land costs in BESS CAPEX*



** Displayed costs represent annualized investment costs as discussed in Section 3.3.1*

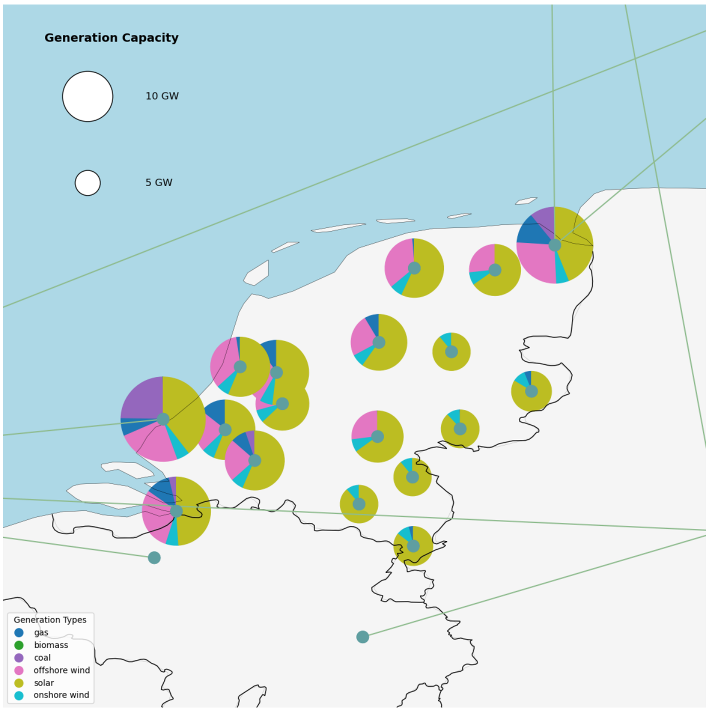
Figure 5.4: Waterfall diagram of scenario cost deltas compared to the base scenario 2023

5.2. Simulation Results 2040 Scenario

This section outlines the simulation results for the BASE, COl, and EXCL scenarios in 2040. Similar to the previous section, it focuses on the spatial distribution of BESS capacity, line utilization, import/export flows, line expansions, and system costs.

For the 2040 scenario, future demand and generation capacities were derived primarily from TenneT projections and supplemented with optimization for certain components. More specifically, renewable capacity data including solar-PV, offshore wind, onshore wind, and nuclear was sourced from TenneT. The other indicators (gas, coal, oil, and biomass) were optimized first in a separate base simulation where these indicators were made extendable. The resulting optimized generation capacities were then fixed for future simulations to ensure each simulation has a common starting point (see appendix C for detailed data).

The energy system of 2040 is projected to have much higher renewable penetration and electricity demand than in 2023. As a result, the role of BESS is expected to be more crucial. The network configuration that serves as a starting point for the 2040 scenarios is shown in figure 5.5. Striking is the installed offshore wind capacity at centrally located nodes due to the way PyPSA-Eur assigns generation to transmission system nodes. While offshore wind farms are physically situated at sea, their power is injected into the grid at designated onshore substations. This results in offshore wind generation being visualized at major inland grid nodes, rather than at its actual geographic location.



* *Nodes size proportionally to their respective generation capacities with higher capacities shown as larger nodes*

Figure 5.5: Overview of the 2040 network

5.2.1. Spatial Distribution of BESS Capacity 2040

With the increased reliance on RES, the 2040 scenarios show different BESS placement patterns compared to 2023. Figure 5.6 shows the spatial distribution of BESS capacity for each of the 2040 scenarios in three sub-figures. The color scale and node size indicate the capacity of BESS allocated at each node. The bigger orange/yellow nodes indicate higher capacities, while smaller purple nodes represent lower capacities.

In the BASE scenario (top map), BESS is evenly distributed across the grid, with higher capacities concentrated in the western and northern regions. These areas are characterized by high renewable energy generation (shown in figure 5.5, including offshore wind, which aligns with localized demand and minimizes long-distance energy transmission requirements.

The COL scenario (middle map), incorporating the cost of land, demonstrates a similar BESS configuration, with only slight changes compared to the BASE scenario. These can be observed with the centrally located nodes where land is more expensive. The total installed BESS capacity is reduced by 4.4% as a result of incorporating land costs.

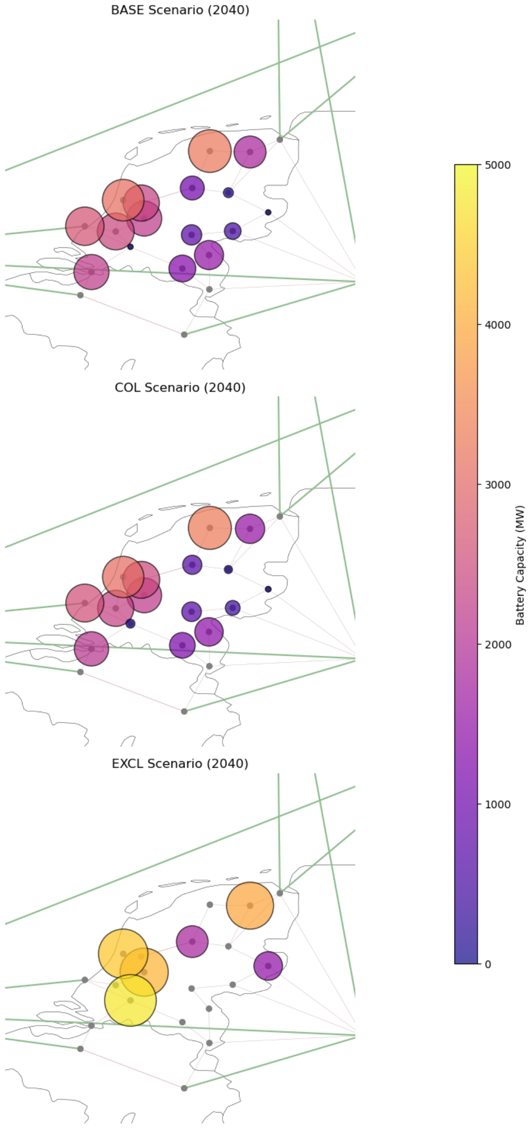
The EXCL scenario (bottom map), constrained by the 2 km exclusion radius, concentrates capacities at fewer, eligible nodes (Table 4.4). Especially buses NL8 and NL9 see a significant absolute and relative increase in BESS capacity allocation for this scenario compared to the BASE. This highlights the intrinsic value of BESS in spatially constrained systems, where even suboptimal placement—being the result of optimization—remains more cost-effective or feasible than alternatives like international grid expansions.

Furthermore, the total installed BESS capacity is much more similar to the BASE model across scenarios in 2040 than for the 2023 simulation, possibly indicating higher system dependencies on BESS. The EXCl scenario shows a decrease of 18.9% installed BESS capacity compared to the base scenario. While figure 5.6 provides a visual overview, table 5.4 quantifies the exact storage capacities assigned to each node helping to understand the magnitude of deployment changes. It also details all relative BESS capacity changes compared to the base scenario. Most notably, buses NL8 and NL9 experience a dramatic increase in BESS capacity in the EXCL scenario, with relative increases of 10,429% and

3,281%, respectively, compared to the BASE scenario. This suggests that, despite not being utilized in the unrestricted optimal configuration, these nodes still provide system-wide benefits when spatial constraints limit alternative placements.

Furthermore, the significant deployment of BESS at previously unused nodes underscores the system's fundamental reliance on a minimum level of storage capacity, even in suboptimal spatial configurations. This highlights that, while BESS placement flexibility is important, its presence in the system remains essential for maintaining grid stability and operational efficiency.

Finally, table D.2 summarizes the expected spatial requirements for each BESS project (assuming constant spatial requirements for BESS between 2023 and 2040). Notably, the spatial requirements for BESS in 2040 are approximately 15 times greater than those in the 2023 base scenario. This increase highlights the substantial land demands for BESS. In the EXCL scenario, these spatial requirements become particularly pronounced at the nodal level, underscoring the critical need for strategic planning to accommodate BESS deployment within the available land constraints.



** Nodes size proportionally to their respective capacities with higher capacities shown as larger nodes*

Figure 5.6: BESS capacity-location map 2040

Table 5.4: Optimal BESS Capacity Data (MW) and Percentage Delta from Base (2040)

Bus	Base [MW]	COL [MW] (% change)	EXCL [MW] (% change)
NL0 0	2196	2168 (-1.3%)	4135 (+88.3%)
NL0 1	1825	1540 (-15.6%)	3964 (+117.2%)
NL0 2	738	687 (-6.9%)	0 (-100.0%)
NL0 3	2208	2104 (-4.7%)	0 (-100.0%)
NL0 4	2640	2575 (-2.5%)	0 (-100.0%)
NL0 5	175	116 (-33.7%)	0 (-100.0%)
NL0 6	0	0 (0.0%)	0 (0.0%)
NL0 7	3094	3055 (-1.3%)	4379 (+41.5%)
NL0 8	45	143 (+217.8%)	4779 (+10429.3%)
NL0 9	43	55 (+27.9%)	1463 (+3281.4%)
NL0 10	1024	658 (-35.7%)	1798 (+75.6%)
NL0 11	3261	3312 (+1.6%)	0 (-100.0%)
NL0 12	1290	1178 (-8.7%)	0 (-100.0%)
NL0 13	491	391 (-20.4%)	0 (-100.0%)
NL0 14	1514	1445 (-4.5%)	0 (-100.0%)
NL0 15	0	0 (0.0%)	0 (0.0%)
NL0 16	2427	2339 (-3.6%)	0 (-100.0%)
NL0 17	2338	2438 (+4.3%)	0 (-100.0%)
Total	**25,310**	**24,205 (-4.4%)**	**20,518 (-18.9%)**

5.2.2. Congestion and Line Utilization 2040

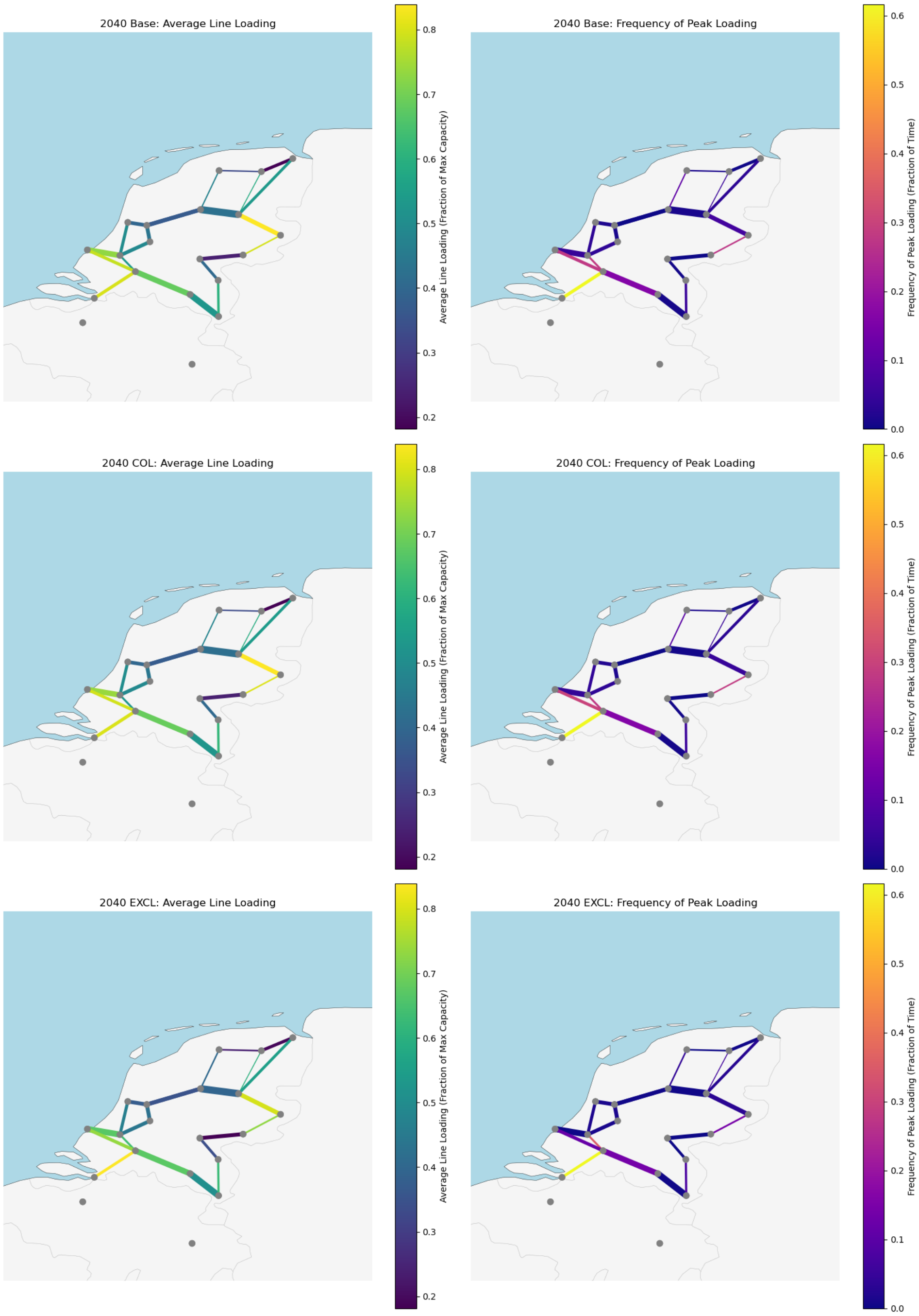
An analysis of the three BESS configurations assessed their impact on net congestion and line utilization. Figure 5.7 presents two sub-graphs: the left shows average line loading as a fraction of maximum capacity (color gradient from blue to yellow), with line thickness indicating absolute capacity. The right sub-graph illustrates peak load frequency, showing how often each line reaches maximum capacity. While both use yellow for the highest values, their scales are independent.

In the BASE scenario (top two maps), the grid demonstrates balanced utilization, with most lines operating below 65% of their maximum capacity on average displayed by the blue and green colored lines. However, some critical transmission lines exhibit consistent peak loading, requiring careful monitoring to prevent overloads (yellow and orange lines). This is seen mainly around nodes with high vRES generation capacity.

While the inclusion of land costs in the COL scenario (middle two maps) shifts BESS placements, the overall loading patterns remain similar to the BASE scenario.

The exclusion scenario (bottom two maps) leads to an uneven BESS distribution. Line 42, which exhibits the highest peak load frequency, experiences an even greater load under the EXCL scenario which might signal the need for line expansions there. Nevertheless, several lines experience reduced average loadings and reduced average stress during peak periods compared to the base model. Similarly to the 2023 simulations, this is found to be the result of flexibility compensation of reduced BESS capacity. The following subsection illustrates that cross-country HVDC connections are particularly expanded, ensuring grid stability despite reduced BESS capacity allocation.

All 2040 scenarios demonstrate a substantial reduction in both average line loading and peak load frequency when compared to the 2023 scenario (tables D.3 and D.4, highlighting the grid's improved capacity to manage energy flows in the future configuration.



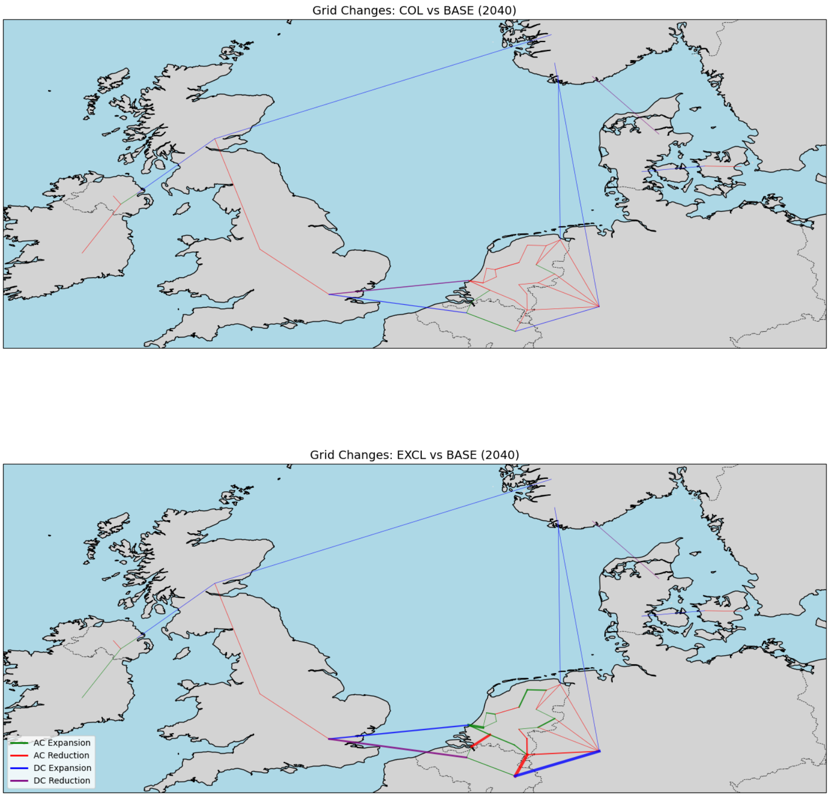
** Line thickness represents line capacity while its color indicates average line loading (left) or peak load frequency (right)*
*** Note that the color scale values are different between the left and right graphs*

Figure 5.7: Congestion and Line loading 2040

5.2.3. Line Expansion and Import/Export Balance 2040

Line Expansion

Since BESS competes with transmission expansion as a flexibility measure, understanding how the different scenarios influence grid reinforcement needs is essential. Figure 5.8 illustrates how grid reinforcements differ under the COL and EXCL scenarios compared to the BASE scenario in 2040. I.e. ”expansions” and ”reductions” refer to a relative change compared to the BASE simulation rather than an expansion or reduction within that simulation. These differences highlight the impact of spatial constraints on the necessity and distribution of AC and DC transmission expansions. It is important to



** The thickness of each line represents the magnitude of its capacity change, with larger capacity changes depicted as thicker lines, regardless of the initial capacity*

Figure 5.8: Line Expansion Network Plot 2040

clarify that a reduction in line capacity is uncommon in reality; however, that is not the intention- here. Instead, the aim is to demonstrate that less capacity is needed in this scenario compared to the base scenario.

1. **AC vs. DC Expansion and Reductions**
   The green lines indicate areas where AC transmission capacity is increased to compensate for local congestion, while red lines show areas where AC capacity is lower than the BASE scenario. The blue lines represent DC line expansions, which appear significantly more prominent in the EXCL scenario, whereas purple lines indicate DC capacity reductions.
2. **Comparison Between COL and EXCL**
   In the COL scenario, transmission expansion is less significant, suggesting that economic land constraints do not force as drastic a shift in transmission strategy. Instead, BESS placement adjusts within available land at relatively moderate costs. In the EXCL scenario, spatial restrictions on BESS placement lead to higher dependency on long-distance energy transport, as reflected in the stronger reliance on DC expansion. This suggests that, in the absence of sufficient BESS placement options, grid expansion becomes the primary flexibility measure.
3. **Key Observations for the Grid**
   Cross-border DC connections are notably reinforced in EXCL, indicating that without optimal BESS siting, flexibility is increasingly sourced internationally. AC expansions show a mixed trend: while some domestic connections are reinforced in EXCL, others—especially between Germany, Belgium, and the Netherlands—are reduced. This suggests that instead of uniformly expanding the in-country grid, EXCL relies on a mix of offshore, cross-border, and selective domestic reinforcements. The stronger dependence on offshore and cross-border HVDC links highlights the impact of limited domestic flexibility on energy imports, with implications for geopolitical security and cost efficiency.

Table 5.5 summarizes the AC- and DC grid expansions compared to the BASE scenario. For clarity, only values > 200 MW have been included. Notably, some major AC expansions occur for the EXCL scenario within the Netherlands. On the other hand, AC capacity between the Netherlands and Belgium reduces significantly compared to the BASE scenario. Finally, a big shift in international DC connection (HVDC) capacity can be seen between GB and NL, and GB and BE.

Table 5.5: Filtered Grid Expansion Comparison (Δ > 200 MW) 2040

Bus 0	Bus 1	Line Type	Type (COL)	Net COL [MW]	Type (EXCL)	Net EXCL [MW]
BE0 0	BE0 1	AC	Expansion	208	Expansion	296
BE0 0	BE0 1	AC	Expansion	208	Expansion	197
BE0 0	BE0 1	AC	Expansion	138	Expansion	296
DE0 0	NL0 15	AC	Reduction	-32	Reduction	-230
DE0 0	NL0 6	AC	Reduction	-93	Reduction	-673
GB2 0	GB2 1	AC	Reduction	-124	Reduction	-210
BE0 0	NL0 3	AC	Expansion	238	Expansion	95
NL0 0	NL0 16	AC	Reduction	-142	Expansion	211
NL0 0	NL0 17	AC	Reduction	-156	Expansion	284
NL0 1	NL0 11	AC	Reduction	-1	Expansion	772
NL0 10	NL0 11	AC	Reduction	-14	Expansion	805
BE0 1	NL0 6	AC	Reduction	-83	Reduction	-1.858
NL0 12	NL0 6	AC	Reduction	-77	Expansion	584
NL0 12	NL0 8	AC	Reduction	-111	Expansion	642
NL0 13	NL0 2	AC	Reduction	-68	Expansion	288
NL0 13	NL0 9	AC	Reduction	-21	Expansion	781
NL0 14	NL0 2	AC	Reduction	-68	Reduction	-446
NL0 14	NL0 6	AC	Reduction	-134	Reduction	-832
NL0 16	NL0 4	AC	Reduction	-462	Expansion	1.523
NL0 17	NL0 7	AC	Reduction	-130	Expansion	625
NL0 3	NL0 8	AC	Expansion	269	Reduction	-1.428
NL0 4	NL0 8	AC	Reduction	-348	Expansion	664
DE0 0	NL0 13	AC	Reduction	-35	Reduction	-236
GB2 2	NL0 4	DC	Reduction	-540	Expansion	808
GB2 2	BE0 0	DC	Expansion	421	Reduction	-1.060
BE0 1	DE0 0	DC	Expansion	305	Expansion	1.661
TOTAL				**-851**		**3.561**

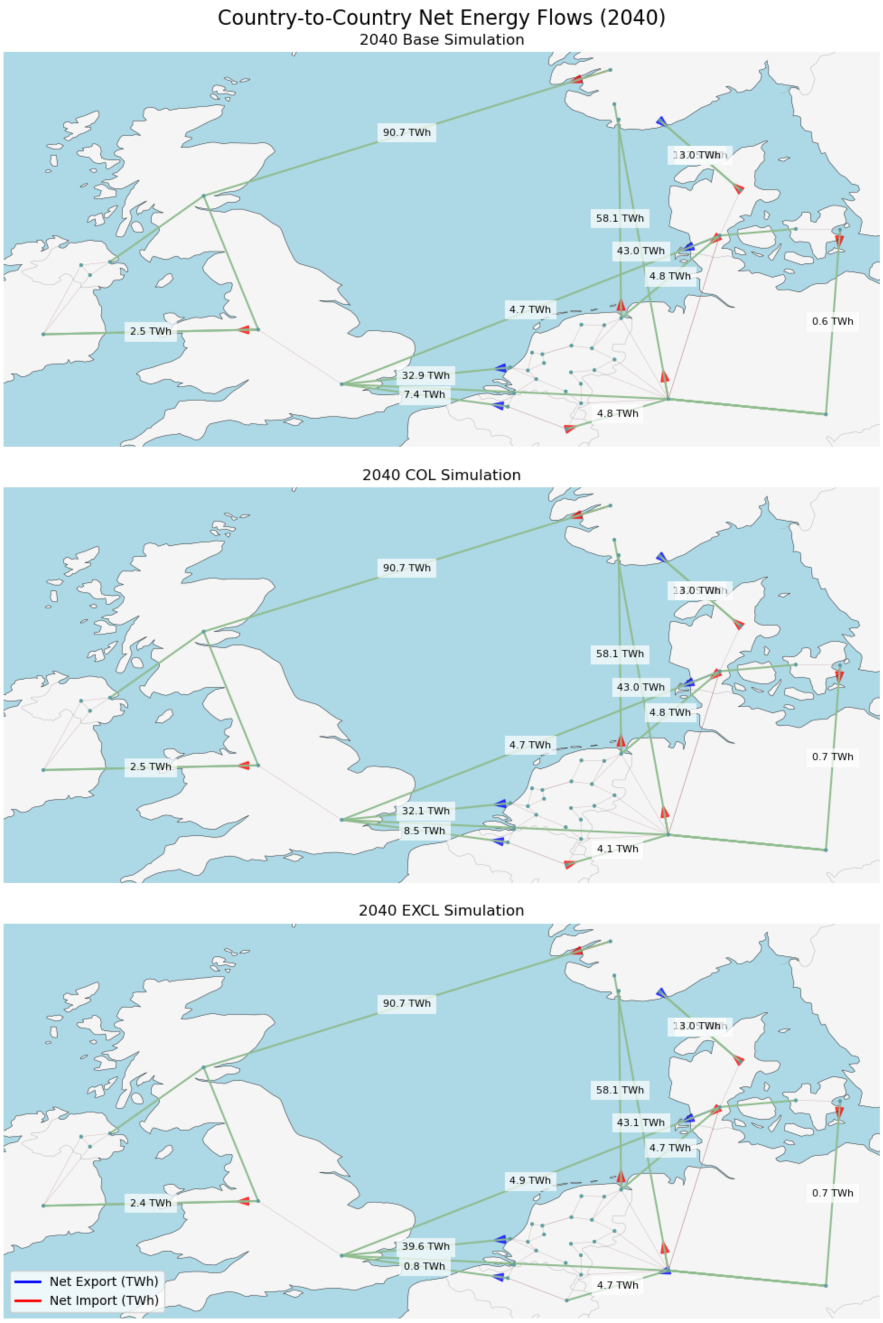
Import and Export

To dive deeper in the significant cross-country DC expansions shown above, an analysis was performed to identify the total import/export balance between each of the considered countries. Figure 5.9 presents the annualized import- and export balance between countries in 2040 for each of the scenarios. The top map represents the BASE scenario, the middle map corresponds to the COL scenario, and the bottom map depicts the EXCL scenario. Each cross-country connection is represented by colored arrows:

- **Blue arrows** indicate the direction of **electricity exports**, pointing toward the country that is sending power.
- **Red arrows** indicate the direction of **electricity imports**, pointing toward the country that is receiving power.

This visualization helps illustrate how power flows shift between countries under different BESS deployment constraints. Further details can be found in Table D.6 which allows for comparison of numeric data. It should be noted that import-/export values < 0.1 TWh are not included in the analysis here to increase overall readability and clarity.

Overall, import- and export dependencies show little change as a result of land costs and imposing exclusion area restrictions. In the EXCL scenario, notable changes are observed between GB and NL, between GB and BE, and between BE and DE. Namely, the Netherlands imports 7.56 TWh more from Britain, while Belgium exports 7.68 TWh more to Britain compared to the base scenario. Germany exports 4.7 TWh to Belgium in this scenario. These findings align strongly with the significant DC expansion between the Netherlands and Britain, and with the DC reduction between Belgium and Britain respectively. A likely explanation for this shift is that the absence of BESS necessitates alternative grid flexibility measures, leading to power flow adjustments. Specifically, the increase in Dutch electricity imports from the UK is partially balanced by a decrease in UK exports to Belgium. To compensate for this reduction, Belgium increases its electricity imports from Germany, ensuring system equilibrium.



** Displayed values represent the net balance between countries (sum of import & export)*

Figure 5.9: Electricity import and -export in 2040

5.2.4. System Costs 2040

Finally, the overall economic implications of the different BESS configurations are examined by assessing their impact on system-wide costs and investment costs in links, lines, and BESS. Figure 5.10 illustrates the cost deltas between the BASE scenario and the COL and EXCL scenarios for the year 2040. The BASE scenario has the lowest system investment costs, reflecting an optimized placement of BESS without spatial or economic restrictions. Each bar represents the change in a specific cost category compared to the BASE scenario, with positive bars indicating cost increases and negative bars indicating cost reductions. The categories include battery investment costs, HVDC and converter capital costs, variable operating costs, AC transmission line capital costs, and a residual category labeled as other costs. The final bar summarizes the total cost delta for each scenario. The results highlight how changes in battery installations impact system-wide costs.

Battery investment costs show reductions in both scenarios. In the COL scenario, the costs are reduced by €10.2M, reflecting slightly fewer battery installations compared to the BASE scenario. In the EXCL scenario, the reduction is even greater at €38.7M, as the exclusion constraints limit battery installations in certain areas. These reductions, however, lead to compensatory increases in other cost categories, particularly HVDC and converter capital costs. In the COL scenario, these costs rise by €22M, while the EXCL scenario sees an increase of €72.1M. This indicates that reduced battery capacity necessitates greater reliance on cross-country HVDC infrastructure.

Variable operating costs, which account for generator operations, also increase in both scenarios. The COL scenario experiences a modest rise of €4.9M, while the EXCL scenario sees a larger increase of €10.2M. These results suggest that as battery installations decrease, the system compensates by relying more on generator output, leading to higher operational expenses. Conversely, line capital costs, which reflect transmission line investments, decrease in both scenarios. The COL scenario sees a reduction of €7.58M, and the EXCL scenario shows an even larger decrease of €14.3M. A plausible explanation for this is the 1858 MW AC line capacity reduction between Belgium and the Netherlands in the EXCL scenario compared to the BASE scenario.

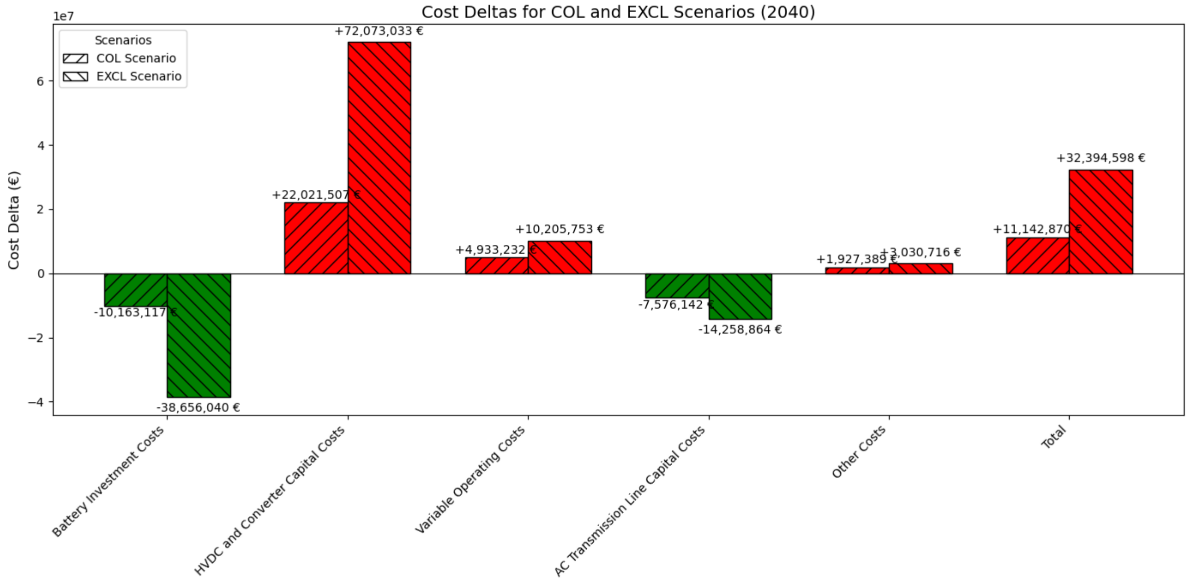
The *other costs* category represents residual elements not explicitly accounted for in the breakdown, such as modeling artifacts or unclassified costs. Both scenarios show small increases in this category, with the COL scenario at €1.9M and the EXCL scenario at €3.M. These residual costs warrant further investigation to clarify their sources and impacts.

In total, the COL scenario results in a modest overall system cost increase of €11.1M, while the EXCL scenario leads to a much larger increase of €32.4M. Both these numbers are however insignificant considering the investments of around €26B. Opposed to the 2023 simulation, investments in links, transmission lines, and BESS are higher than the BASE values for both scenarios in 2040. The waterfall diagram illustrates that the main cost drivers are the HVDC- and converter CAPEX.

Table 5.6: System cost results for 2040 Scenarios

Simulation	BASE	COL**	EXCL**
Total system costs	€ 85.0B	€ 85.0B	€ 85.0B
Delta (compared to base)	–	€ 11.1M	€ 32.4M
Investments in links, lines and BESS	€ 25,7B	€ 25,7B	€ 25,7B
Delta (compared to base)	–	€ 4,3M	€ 19,2M

** Displayed costs represent annualized investment costs as discussed in Section 3.3.1*
*** Include land costs in BESS CAPEX*



** Displayed costs represent annualized investment costs as discussed in Section 3.3.1*

Figure 5.10: Waterfall diagram of scenario cost deltas compared to the base scenario 2040

5.3. Conclusion Chapter 5

This chapter examined the results of the optimization model, focusing on how spatial constraints and land costs influence BESS placement in the Dutch high-voltage grid. By evaluating the 2023 and 2040 scenarios under three configurations—BASE (unrestricted), COL (including land costs), and EXCL (applying spatial exclusions)—the analysis provided critical insights into the systemic trade-offs in battery deployment.

The 2023 simulations revealed that spatial constraints significantly affect BESS placement, with the EXCL scenario leading to a 43.2% reduction in total installed capacity due to the imposed 2 km radius exclusion around HV substations. The relocation of BESS to fewer eligible nodes increased reliance on transmission infrastructure and strategic nodes, although the overall system investment costs remained largely unaffected. The COL scenario, which incorporated land costs, had a marginal impact on BESS capacity distribution, with only a 9% reduction. This suggests that land pricing alone does not strongly dictate BESS placement in the current regulatory and economic landscape.

In the 2040 scenarios, the impact of spatial exclusions remained significant but was less pronounced than in 2023, with an 18.9% reduction in BESS capacity under the EXCL scenario. This reflects the growing system dependence on storage as renewable penetration increases. Unlike in 2023, where BESS could be eliminated at certain nodes with limited system-wide consequences, in 2040, the optimization model allocated significant BESS capacities at eligible nodes, underscoring its necessity for grid stability. Despite these shifts, system investment costs remained relatively stable across scenarios, with minor cost increases (€11M in COL and €32M in EXCL) compared to the overall system expenditure of approximately €85B. This demonstrates that while spatial constraints influence BESS distribution, they do not drastically alter.

The analysis of line utilization and congestion provided further insight into the systemic effects of BESS placement. While spatial constraints resulted in moderate shifts in congestion patterns, the average line loading remained consistent across scenarios. However, in 2040, there was a noticeable reliance on grid expansions as a result of the increased import reliance from the Netherlands on the UK. Particularly in the EXCL scenario, where the model increased HVDC transmission capacity to compensate for reduced BESS flexibility. This highlights a potential trade-off between distributed storage deployment and long-distance energy transport solutions.

The findings emphasize that while spatial constraints shape BESS allocation, they do not significantly alter system costs, congestion patterns, or the fundamental role of storage in maintaining grid stability. The resilience of the Dutch HV grid to spatial and economic restrictions suggests that BESS deployment strategies should focus on optimizing placement within existing land-use policies while ensuring sufficient spatial flexibility to accommodate future storage needs.

The next chapter will further contextualize these results within broader energy system planning and policy discussions, evaluating the long-term implications of BESS placement decisions for grid reliability, investment strategies, and regulatory frameworks.

6 Discussion

The outcomes of this research highlight relations between spatial, economic, and technical factors influencing the placement of BESS in the HV grid of the Netherlands. This chapter reflects on these findings, considering their broader implications for energy system planning, multi-actor perspective, and policy, as well as the sensitivities within the model's assumptions. Furthermore, it also reflects on the research process to shed light on the quality of results. The last chapter zoomed in on the specific results for 2023- and 2040 optimized energy system networks. This chapter serves to interpret not only those results but also those retrieved in earlier chapters from literature and interviews.

6.1. Reflection on the Results

6.1.1. Reliance on BESS

Academic literature emphasizes an anticipated growth on BESS reliance in future electricity systems (Schmidt & Staffell, 2023; Yang et al., 2020). The model results align with this and demonstrate a clear and growing reliance on BESS as the energy system transitions to 2040, with significant differences in sensitivity to spatial constraints between the two years. In the 2023 exclusion scenario, only 56.7% of the base BESS capacity was retained, compared to 81.1% in 2040. Although the line load analysis uncovered that limiting BESS placement options does not necessarily decrease line loading and peak load frequencies, this did result in a higher cross-country interdependency requiring costly HVDC connection expansion increasing overall expenses in 2040.

The model outcomes indicate that accommodating the anticipated BESS capacity in 2040 will require significant space, especially around industrial clusters (Nationaal Programma Verduurzaming Industrie (NPVI), n.d.), with some nodes exceeding 2 km² of land area. Established literature emphasizes the benefits of co-locating storage and renewable generation to minimize line losses, balance local energy flows, and reduce reliance on long-distance transmission (Castro & Espinoza-Trejo, 2023; Hazra et al., 2015). This insight combined with the significant spatial requirement and limited space availability in the Netherlands (RVO, 2024a), underscores the importance of proactive planning to ensure sufficient land availability for BESS deployment near critical nodes.

Furthermore, the results reveal the limited impact of suboptimal placement in the short term (2023) on system-wide investment costs. The relatively low BESS capacities, and abundance of dispatchable generation capacity in 2023 reduce the cost penalties of spatial constraints, suggesting that strict prioritization of specific nodes may not be immediately necessary. However, one important reflection on the 2023 simulations is based on the high marginal costs for fossil-based generation. Namely, the high marginal costs were incorporated to simulate the status-quo electricity system with BESS in the system. Since lower marginal costs resulted in a network configuration with no BESS capacity installed, the marginal cost parameter was increased to ensure that BESS deployment was incorporated into the system. This choice impacted not just system-wide BESS capacities, but also the variable operating costs of generation. Although these marginal costs are not realistic, they allowed the simulation of BESS allocation which was the main focus of this research.

TenneTs concerns about the impact of large-scale BESS on the grid, especially regarding peak loads and infrastructure scaling, are addressed by these findings. The 2040 results show that BESS capacities per station far exceed current project scales, indicating that early fears about localized grid impacts may be overstated. However, coordinated planning remains critical to ensure that these high-capacity deployments are aligned with grid requirements and land-use policies. A long-term strategy could benefit from prioritizing nodes with high renewable generation capacity and demand concentrations, as this has the potential to reduce overall system investments and improve resilience. However, the effectiveness of this approach depends on various factors, including spatial constraints, evolving market dynamics, and technological advancements.

Finally, academic literature highlights the trade-offs among flexibility solutions, including different storage technologies and alternatives like demand-side management (Möst et al., 2021; Schmidt & Staffell, 2023). While BESS offers rapid response and modularity, its limited duration makes it less suited for long-term storage compared to power-to-gas or hydro. Similarly, demand-side management and sector coupling provide cost-effective flexibility under certain conditions, reducing reliance on storage.

This study underscores that BESS can enhance grid reliability but it does not quantify its effectiveness when integrated with complementary flexibility mechanisms like, long-duration storage, demand-side management, and sector coupling. Future research should quantify the optimal mix of these solutions, balancing spatial and economic trade-offs for long-term system planning (Möst et al., 2021).

6.1.2. HVDC Connectivity

The reliance on HVDC interconnections becomes particularly evident in the 2040 exclusion scenario, where spatial constraints necessitate a shift in energy trade patterns. The Netherlands increased electricity imports from Great Britain by 7.56 TWh, requiring 808 MW expansion upgrades to cross-border HVDC connections. This finding highlights the interconnected nature of European energy markets and the role of international energy flows in mitigating domestic spatial constraints.

While HVDC connections offer an effective flexibility mechanism, their implementation is associated with high costs and logistical challenges. In the 2040 EXCL scenario, HVDC line expansion costs increased by €72 million annually compared to the base scenario. These costs are significant, especially when considering the labor-intensive construction process and geopolitical risks associated with cross-border dependencies. This raises critical questions within the ongoing discussion in academic literature about whether reliance on HVDC links is a sustainable long-term strategy, particularly in light of ongoing geopolitical tensions and the push for energy independence within the EU (Imdadullah et al., 2021). Alternative mechanisms, such as ATR85 contracts, could reduce peak loading and alleviate the need for costly reinforcements. Policymakers should explore these options as part of a comprehensive congestion management strategy.

On the other hand, the EXCL scenario revealed a reduction in average line loading and peak load frequency across the Dutch HV grid. This suggests that international interconnections effectively alleviate local congestion, supporting the argument for HVDC links as a valuable, albeit costly, alternative to domestic grid reinforcements. However, these results should not detract from the importance of developing a robust national BESS deployment strategy. BESS solutions are more scalable and adaptable, offering localized flexibility without the need for complex international infrastructure and agreements.

In conclusion, while HVDC links provide critical flexibility in spatially constrained scenarios, they should be viewed as a complementary measure rather than a primary solution. Policymakers must weigh the trade-offs between investing in international interconnections and prioritizing domestic storage solutions like BESS to ensure a resilient and cost-efficient grid.

6.1.3. Market Dynamics

The deployment of BESS is influenced by the competing priorities of TSOs, market participants, and regional governments. TSOs prioritize grid stability and resilience, favoring distributed BESS deployments to manage regional demand and peak loads effectively. Market participants, however, are driven by cost-efficiency and time-to-market considerations. For market participants, this implies that practical factors, such as land availability and permitting, can guide immediate decisions without significantly impacting system performance.

The findings also highlight the role of regional governments in addressing land-use conflicts. Spatial constraints modeled in this study, such as exclusion zones, demonstrate the potential impact of land availability on BESS placement. From the perspective of TenneT as TSO, policymakers should proactively incorporate these insights into spatial planning processes to ensure sufficient land is allocated for storage infrastructure near critical nodes. This aligns with recent studies emphasizing the importance of integrating energy system planning and spatial planning to support the deployment of renewable energy technologies (Loomans & Alkemade, 2024; N. Wang et al., 2020).

From a market perspective, the results provide clarity on the economic implications of BESS placement. The relatively small cost differences across scenarios suggest that market parties can prioritize practical considerations in the short term. However, the insights into preferential nodes and their alignment with renewable generation provide TSOs with a foundation for long-term strategy development. Such strategies should balance the interests of market participants and regional governments while ensuring grid resilience and cost-effectiveness. One example approach for this could be the co-investment in grid-connection cables by the TSOs at preferential locations.

Finally, this research underscores the importance of coordination among stakeholders. A national BESS allocation strategy that aligns the priorities of TSOs, market participants, and regional governments would address multi-dimensional uncertainties and provide a clear framework for future BESS deployment. This is particularly important as the grid evolves to accommodate higher renewable penetration and more stringent decarbonization targets.

6.1.4. Broader implications for congestion and Policy

Congestion management emerged as a key area of divergence between stakeholder priorities. TSOs, such as TenneT, regard congestion as a critical grid stability issue that requires proactive intervention, while market actors prioritize the overall financial viability of BESS projects, often focusing on short-term revenue streams rather than system-wide congestion relief. The modeling results indicate that even under suboptimal BESS placement scenarios, congestion levels remain manageable in both 2023 and 2040. This suggests that, in the near term, market-driven BESS deployment is unlikely to exacerbate grid congestion significantly. However, as the energy system transitions towards higher shares of renewable energy, the interaction between congestion, BESS placement, and market incentives will become increasingly relevant. Moreover, these results contradict current grid operator signals about the significant congestion in the electricity grid of the Netherlands (Pató, 2024). This discrepancy can be explained by the grid typology and line loading constraints used for this research. Namely, only the UHV grid was considered which generally shows less congestion than connections operating at lower voltage levels (Netbeheer Nederland, 2023). Furthermore, this study does not adopt the N-1 principle, which represents a more strict constraint on line loading, while this is considered for real-world grid analyses.

Another crucial policy consideration is the role of permitting and spatial planning in BESS deployment. Current permitting procedures can be slow and restrictive, leading to delays that impact the feasibility of storage projects. Streamlining permitting processes while maintaining spatial flexibility is essential to ensuring that BESS can be deployed in locations where it is most effective for grid stability. Expedited permitting for strategically important BESS installations—such as those located near renewable generation hubs or congested grid nodes—could enhance the efficiency of deployment while avoiding unnecessary administrative barriers.

The deployment of approximately 20 GW of BESS across all modeled scenarios reinforces the critical role of storage in supporting the energy transition. Even when spatial and economic constraints were introduced, the model consistently allocated significant BESS capacities, highlighting storage as a fundamental component of future flexibility strategies. However, the placement and distribution of this capacity are equally important. A widely distributed storage network not only supports localized balancing but also enhances system resilience by reducing reliance on centralized interventions during peak load periods or contingency events.

Furthermore, cross-border electricity flows played a notable role in mitigating congestion in certain scenarios, particularly in 2040 when higher renewable penetration increased reliance on interconnections. This suggests that international coordination on storage and congestion management strategies could provide additional flexibility, reducing the need for costly domestic grid reinforcements. Policymakers should consider the potential for cross-border storage coordination as part of broader European electricity market integration efforts.

As the Dutch electricity grid evolves, ensuring that BESS deployment aligns with congestion management goals will require a combination of regulatory adjustments, market-based incentives, and strategic planning. A well-integrated approach that considers both market dynamics and system-wide stability requirements will be essential in maximizing the benefits of storage while minimizing unnecessary infrastructure costs.

6.2. Reflection on the Research Process

6.2.1. Sensitivity and Model Assumptions

Sensitivity analyses and underlying model assumptions play a critical role in shaping the outcomes and insights derived from this research. While the model provides a robust framework for evaluating the spatial, economic, and technical factors influencing BESS deployment, the results are inherently dependent on several assumptions and simplifications that warrant careful consideration.

Sensitivity

The sensitivity of BESS allocation to changes in land-use constraints and costs was analyzed through scenario comparisons. The results indicate that BESS placement is highly sensitive to even minor economic or spatial variations. In the COL scenario, where land costs were introduced, only small changes in the cost structure led to noticeable shifts in BESS placement, though the system-wide investments remained nearly unchanged. This suggests that while individual BESS locations may be influenced by financial considerations, the overall investment cost related to AC- and HVDC transmission capacity and BESS is largely insensitive to land price variations.

Similarly, grid congestion and peak loading patterns were found to be relatively stable across scenarios. Despite significant changes in BESS allocation under the EXCL scenario, key system metrics—such as average line loading and peak load frequency—remained consistent. This indicates that spatial constraints influence the geographic distribution of BESS, but do not introduce substantial operational challenges in terms of transmission congestion.

While this study provides insights into the impact of land costs and exclusion zones, a more comprehensive sensitivity analysis could further improve understanding of the system's robustness under different conditions. Future research could explore variations in renewable energy penetration levels, alternative energy storage technologies, and demand growth scenarios. This would provide a broader perspective on the interplay between flexibility means like BESS deployment, international grid expansion, or for instance demand control.

Assumptions

This study relies on several modeling assumptions that impact the interpretation and applicability of its findings.

First, demand and renewable generation profiles for 2023 and 2040 are based on static projections from the II3050 NAT scenario, which assumes ambitious electrification and decarbonization pathways. While this aligns with Dutch policy goals, it may overestimate future electricity demand and supply capacities if technological adoption slows or policies shift. Additionally, demand regionalization follows a 60/40 GDP-to-population weighted approach in PyPSA-Eur, which oversimplifies real-world demand patterns. Especially in regional infrastructure allocation policy, accurate demand estimates are highly important (N. Wang et al., 2020). Future research could therefore add more depth to this research field refining projections by incorporating adaptive demand models and regionally specific energy consumption patterns.

Secondly, in this study, PyPSA-Eur does not explicitly model income streams; rather, it incorporates a break-even financial assumption by annualizing capital expenditures using an annuity factor. In essence, the model assumes that the revenues—primarily derived from the day-ahead market—are calibrated to exactly offset the annualized costs, meaning that incomes are implicitly set equal to expenses (plus the cost of capital) to achieve a break-even system optimization. This normative approach simplifies financial modeling but therefore overlooks detailed revenue mechanisms that exist in real-world operations. Representing these real-world operations would likely result in a lower capacity of BESS. Market cannibalization would occur at a lower BESS adoption level and market parties would not be inclined to invest if no profits can be made. Looking ahead, future research could refine this assumption by adjusting the interest rate to include a profit margin, thereby allowing the model to account for desired returns on investment and enhancing its practical relevance.

Third, spatial resolution is simplified through node aggregation, reducing computational complexity but limiting geographic precision. Exclusion zones are applied at the node level, rather than substation-level land-use constraints, potentially misaligning modeled and real-world feasibility. When nodes represent real-world station locations, optimal BESS allocation under spatial constraints would provide deeper and more actionable insights. Future work could therefore integrate real substation coordinates and GIS-based zoning regulations (Appendix D outlines a setup for this approach).

Fourth, the model operates under a nodal pricing framework that calculates locational marginal prices at high spatial resolution. This approach efficiently optimizes power flows and manages local congestion, leading to a highly detailed spatial allocation of BESS. However, in reality, Europe's electricity markets are structured on a zonal basis, where re-dispatch mechanisms and aggregated congestion pricing tend to smooth out local price differences. As a result, the nodal pricing assumption in the model may overstate the benefits of localized congestion management and could influence the optimal siting of BESS by favoring locations that appear more economically attractive than they might be under zonal conditions. Future research should therefore incorporate zonal pricing schemes and explicitly model redispatch costs, allowing for a direct comparison of how different market structures affect system costs, congestion management, and the spatial distribution of storage assets. Such an approach would yield more policy-relevant insights by aligning the model more closely with the operational realities of European electricity markets.

Finally, the exclusion of stakeholder behavior and ancillary services simplifies the model but limits its practical applicability. BESS provides essential services such as frequency regulation, which was not explicitly modeled. Similarly, decision-making assumes rational and optimal investment behavior, whereas real-world deployment is influenced by regulatory delays, permitting challenges, and stakeholder opposition (Yang et al., 2020). Future research should incorporate agent-based modeling or institutional feasibility assessments to better reflect deployment constraints.

6.2.2. Limitations

While this study provides valuable insights into the spatial and economic constraints of BESS placement, several limitations must be considered when interpreting results and shaping future research.

- **Static snapshots instead of dynamic modeling:** This study models two static years (2023 and 2040) rather than a continuous transition. While these snapshots capture short- and long-term system conditions, they do not reflect gradual policy shifts, infrastructure investments, or evolving flexibility solutions over time. As a result, BESS deployment patterns may be over- or underestimated. Future studies should adopt dynamic energy transition modeling to assess phased BESS integration, providing insights into investment timing and technology shifts.
- **Simplified temporal considerations in BESS deployment:** The model does not account for deployment delays caused by permitting, stakeholder negotiations, or regulatory processes. This simplification likely results in an overoptimistic estimation of deployment speed. Future research could integrate empirical permitting timelines and regulatory constraints to provide a more realistic depiction of investment lags and their impact on system adequacy.
- **Marginal cost representation and sensitivity analysis:** The model uses high CO_2 costs (€400/tonne) to emphasize conditions under which BESS would be deployed immediately. While this highlights the benefits of early storage investment, it may exaggerate economic incentives compared to real-world market conditions.
- **Spatial abstraction in node aggregation:** The model aggregates nodes for computational feasibility, simplifying geographic representation. This reduces precision, particularly in land-use exclusions, which are applied at the node level rather than around substations. Future studies

should incorporate GIS-based zoning data and real substation locations to improve spatial accuracy.

- **Exclusion of MV/LV networks:** The analysis focuses on the high-voltage grid (220 kV & 380 kV), excluding interactions with medium- and low-voltage networks. This limits insights into distributed storage and local congestion management. Future research should integrate multi-voltage BESS modeling to assess system-wide flexibility impacts and decentralized investment strategies.
- **Simplified spatial constraints:** Land availability is modeled using predefined exclusion zones and broad land-use categories (e.g., NATURA 2000, urban areas), but factors like topography, private land ownership, and marginal land availability are not considered. This may lead to either an over- or underestimation of practical land constraints. Future studies should refine spatial constraints using detailed GIS-based land-use competition models.
- **Reliance on a single demand and generation scenario:** The 2040 projections rely on TenneT's II3050 NAT scenario, which assumes high electrification and decarbonization. If actual demand growth deviates, BESS requirements may be misrepresented. Future work should explore multiple demand and generation scenarios to improve robustness and identify flexibility needs under different policy pathways.
- **Nodal pricing assumption and market structure:** The model applies a nodal pricing structure, allowing for high spatial resolution of congestion effects. However, most European electricity markets operate under a zonal framework. This may overestimate the concentration of BESS near congested nodes, as redispatch costs in a zonal market would be distributed more broadly. Future research should compare nodal and zonal pricing approaches to assess their impact on system costs and BESS allocation.
- **Static land cost assumptions:** Land costs are treated as regionally fixed and do not account for market-driven fluctuations, inflation, or competitive land bidding. This could underestimate long-term cost volatility. However, since land costs were not found to impact the system significantly, this limitation would not form the basis for further research.
- **Institutional and behavioral constraints:** Due to the lack of standardized BESS regulations in the Netherlands and the high regional variability in land-use policies and guidelines, this study excluded institutional factors from its scope. Nevertheless, institutions can significantly impact BESS placement (Lombardi et al., 2020; Pedersen et al., 2021), for which follow-up research could include them. Table D.8 in the appendix provides a starting point for this based on regional policy documents for the Netherlands. Furthermore, the model assumes rational decision-making, optimizing investment costs without considering socio-political barriers such as local opposition, permitting delays, or regulatory uncertainties. These constraints may prevent optimal BESS placement in practice. Future research could integrate agent-based modeling and institutional feasibility assessments to reflect real-world decision-making dynamics.

Each of these limitations affects different aspects of the study's findings:

- The lack of dynamic modeling reduces validity in capturing real-world transition dynamics, making results more indicative of single end-state system conditions rather than the pathways leading there.
- Spatial abstraction in node aggregation reduces geographic precision, meaning the results should be interpreted as generalized placement trends rather than precise site recommendations.
- The exclusion of MV/LV grids limits generalizability, as distribution-level storage interactions could influence system-wide flexibility.
- Reliance on a single demand scenario introduces uncertainty in robustness, as alternative electrification pathways may lead to different BESS needs.
- The nodal pricing assumption may overestimate the concentration of BESS deployments, making results less directly transferable to European market conditions.
- Economic land-use simplifications may lead to an underestimation of long-term cost fluctuations, affecting investment feasibility assessments.

- Ignoring socio-political constraints reduces the practical applicability of results, since institutional and regulatory challenges could delay or prevent optimal BESS placement strategies.

While these limitations do not invalidate the study's conclusions, they emphasize the need to interpret results within the specific modeling assumptions used. Future research can build on these findings by incorporating dynamic energy transition modeling, higher spatial granularity, diversified demand scenarios, and socio-political feasibility assessments.

6.2.3. Recommendations

Based on the findings of this research, several recommendations are proposed to support the cost-effective and spatially efficient deployment of BESS while addressing system flexibility needs and land-use constraints.

1. A national BESS deployment roadmap should be developed in collaboration with TenneT, policymakers, and market participants. This roadmap should outline both short-term and long-term strategies for optimizing BESS placement. In the short term (2025–2030), deployment should be distributed across HV substations to mitigate congestion and improve flexibility, with an initial capacity limit per station to prevent localized overloading. In the long term (2030–2040), deployment should be prioritized at stations with high projected demand growth and substantial renewable energy integration, particularly those with significant offshore wind, solar PV, and interconnection capacity. The roadmap should remain flexible and be updated iteratively based on market conditions, grid expansion progress, and evolving land-use regulations.
2. Spatial planning should be integrated into BESS policy frameworks to reduce uncertainty and permitting delays. Clear zoning regulations should be introduced to identify pre-approved BESS deployment areas, ensuring land availability near HV substations and renewable energy hubs while minimizing conflicts with protected areas such as NATURA 2000 zones. Spatial prioritization frameworks should be developed to align with grid needs, and incentive mechanisms, such as land leasing programs or zoning exemptions, should be introduced to encourage cost-optimal BESS placement.
3. BESS planning should be aligned with national grid expansion strategies to ensure that storage deployment complements rather than competes with planned infrastructure investments. BESS should be prioritized in areas where grid expansion is limited due to spatial constraints, allowing it to serve as a local flexibility solution where transmission reinforcements are infeasible. Coordination with the II3050 infrastructure roadmap should ensure that BESS acts as a congestion mitigation tool in regions with projected grid constraints. Additionally, flexibility trade-offs should be analyzed by comparing the cost-effectiveness of BESS versus HVDC expansion, ensuring that system investments remain economically justified.
4. Economic and market conditions should be improved to support BESS investments, as financial feasibility remains uncertain under current market structures. Revenue mechanisms should be expanded beyond energy arbitrage to include capacity market participation and ancillary service remuneration, ensuring that BESS operators can secure stable revenue streams. Investment conditions should be stabilized by providing clear regulations on grid connection procedures, congestion pricing, and revenue stacking, reducing uncertainty for developers. Additionally, land cost subsidies should be evaluated in areas where high land prices could discourage the cost-optimal placement of storage assets.
5. Regulatory and institutional coordination should be strengthened to address permitting bottlenecks and grid access challenges. A coordinated BESS permitting framework should be established between TSOs, DSOs, and regional authorities, ensuring that storage applications are processed efficiently and transparently. National and EU-level policies should be aligned to facilitate cross-border storage integration, improving market clarity for large-scale BESS investments. Additionally, the regulatory role of BESS in congestion management should be clarified, ensuring that storage deployment supports system-wide flexibility objectives rather than merely optimizing for arbitrage profits.

7 Conclusion

In this chapter, the conclusions of this master thesis are provided. This research investigated the relation between spatial, economic, and technical factors influencing the optimal placement of BESS in the Dutch HV grid. Through a combination of optimization modeling, interviews, and literature review, the study explored how BESS placement is shaped by spatial constraints, cost-of-land considerations, and technical grid requirements. This chapter summarizes the main findings, highlighting their implications and relevance to the research questions. Then Section 7.3 provides implications for policy and practice. Section 7.4 provides an evaluation of the learning process during this thesis time. Subsequently, section 7.5 links the conclusions of this research to the CoSEM Master program. Finally, section 7.6 lists a few suggestions for future research.

7.1. Answering the Sub-Research questions

SQ1: *What are relevant considerations in the process of BESS development and -placement according to academic literature and real-world experts in the Netherlands?*

Stakeholder interviews and literature revealed 18 key phases by which BESS development is shaped, six of which directly affect spatial decision-making: site selection, land acquisition, permitting, zoning assessments, environmental assessments, and grid connection. The following considerations stood out:

1. **Institutional Barriers:** A recurring theme in the interviews was the impact of permitting delays and zoning plan changes on project timelines. Stakeholders emphasized that the lack of streamlined and consistent permitting processes is a significant barrier to timely BESS deployment. These delays are especially pronounced in areas near protected zones or regions with competing land uses, where regulatory hurdles can stall projects for extended periods. While academic literature often does not explicitly address these institutional delays, their practical importance was underscored by multiple interview participants.
2. **Proximity to Grid Infrastructure:** Developers consistently expressed a preference for sites near HV substations to minimize grid connection costs. Locations within a 2 km radius of substations were highlighted as particularly advantageous, as cable costs increase significantly with distance. This finding aligns closely with the assumptions used in the modeling framework, which prioritized nodes with strong grid connectivity. The emphasis on proximity reflects a practical trade-off between technical feasibility and economic efficiency in BESS placement.
3. **Stakeholder Misalignment:** The interviews revealed significant differences in the priorities of key stakeholders. TSOs, such as TenneT, prioritize long-term grid stability, congestion mitigation, and system-wide optimization, while market actors focus on profitability and quick returns. For example, TSOs often require more time to evaluate the grid impacts of proposed BESS connections, whereas developers aim to secure approvals as quickly as possible to minimize financial risks. These misalignments create tensions that can delay deployment and reduce overall system efficiency. Collaborative frameworks that align stakeholder incentives and priorities could

mitigate these issues.

4. **Land Trade-offs:** While land costs themselves were not viewed as a primary driver of site selection, the availability of land emerged as a critical factor. Interviewees noted that land-use conflicts, such as competing demands for agricultural, residential, or industrial development, can limit the pool of viable sites for BESS. This finding reinforces the need for proactive spatial planning to balance competing land uses and ensure sufficient space for future storage infrastructure.

By integrating these considerations, the research aligns with and extends existing literature, providing a framework for addressing both technical and socio-economic barriers to BESS deployment.

SQ2. *What is the impact of imposing restrictions related to competing land use and exclusion areas on the optimal placement of BESS?*

The modeling results indicate that spatial constraints, modeled as exclusion zones, influence the optimal placement of BESS in the Dutch HV grid. By restricting the availability of land for BESS deployment, exclusion zones force a redistribution of storage capacity, concentrating deployment at a smaller number of high-priority nodes. This section outlines the key impacts of these constraints as derived from the modeling framework and stakeholder insights.

1. **Reduction in Total Installed Capacity:** Spatial constraints were associated with a notable reduction in total installed BESS capacity, particularly in the 2023 EXCL scenario, where capacity was 43.2% lower than in the base scenario. By contrast, the impact was less pronounced in 2040, with only an 18.9% reduction. This difference reflects the growing reliance on BESS in a renewable-dominated energy system and suggests that as demand for flexibility increases, spatial constraints will have proportionally less influence on overall capacity deployment.
2. **Concentration of Deployment:** The inclusion of exclusion zones resulted in the concentration of BESS capacity at fewer nodes, such as NL011. These nodes are characterized by high renewable generation potential and strong grid connectivity, making them strategic locations for storage deployment. This finding underscores the importance of co-locating BESS with renewable energy sources to balance localized energy flows and minimize long-distance transmission requirements.

   The model results align with practical insights from stakeholders, who noted that land-use constraints often limit the availability of suitable sites near renewable generation hubs. This creates a tension between the need for spatial optimization and the realities of competing land uses, such as agriculture or urban development.
3. **Grid Resilience and System Costs:** Despite the significant reduction in installed capacity, the Dutch HV grid demonstrated remarkable resilience under spatial constraints. Congestion levels remained manageable, and the system adapted by redistributing energy flows through alternative nodes and interconnections. However, this adaptability came at a cost: system costs increased by €32.4 million annually in 2040 under the EXCL scenario. This increase, while modest in relative terms, highlights the financial implications of spatial constraints and the need for strategic planning to minimize cost penalties.
4. **Impacts on Interconnections:** The exclusion scenarios also revealed an increased reliance on cross-border interconnections, particularly HVDC links with Great Britain. For instance, electricity imports from Great Britain to the Netherlands increased by 7.56 TWh in the 2040 EXCL scenario. While these interconnections effectively mitigated local spatial constraints, they introduced new dependencies and higher costs associated with HVDC expansion. This finding emphasizes the need for balanced approaches that prioritize domestic storage deployment while leveraging interconnections as a complementary flexibility mechanism.
5. **Spatial Planning Challenges:** Stakeholder feedback highlighted the practical challenges of integrating spatial constraints into energy system planning. For example, protected areas such as Natura 2000 zones and urban expansion plans often conflict with the need for large-scale energy storage infrastructure. The results of this research suggest that policymakers must proactively identify and prioritize suitable sites for BESS deployment to reduce the impact of land-use conflicts and streamline permitting processes.

SQ3. *What is the impact of including the cost of land in the consideration of BESS placement in the model?*

The inclusion of regional land costs in the COL scenario had a relatively minor impact on the optimization outcomes, with a slight increase in peak line loading frequency in central regions (where prices were highest). This aligns with stakeholder insights that land costs are secondary to permitting delays and technical constraints. However, integrating land costs provided valuable sensitivity analysis, demonstrating that even under high-cost assumptions, optimal BESS placement strategies remain robust.

7.2. Answering the main Research Question

This research aims to answer the main research question:

What is the impact of spatial constraints and economic land use considerations on the optimal placement of large-scale battery storage systems (BESS), from the perspective of a TSO, in the Dutch High-Voltage grid?

This research suggests that spatial constraints and land-use considerations play an important role in shaping the deployment of BESS in the Dutch HV grid. By integrating spatial exclusion zones, land costs, and technical grid requirements into the modeling framework, the study provides insights into how these factors influence the location, capacity, and overall system costs of BESS placement. The key findings are summarized below.

1. **Spatial Constraints Drive Concentration of BESS Deployment**

   The inclusion of spatial constraints, such as exclusion zones for Natura 2000 and urban land-use restrictions, significantly impacts the distribution and concentration of BESS capacity. In the EXCL scenarios, capacity was concentrated at fewer, high-priority nodes with strong grid connectivity and high renewable generation potential (e.g., offshore wind hubs like NL011).

   In 2023, spatial constraints led to a 43.2% reduction in total installed BESS capacity compared to the base scenario, reflecting the limited reliance on storage in the current grid. By contrast, the 2040 EXCL scenario showed only an 18.9% reduction, demonstrating the system's growing dependence on BESS to balance renewable energy generation and support grid flexibility. This finding underscores the need for long-term spatial planning to ensure sufficient land availability at critical nodes to accommodate the increasing demand for storage.

2. **Limited Impact of Land Costs on System Optimization Outcomes**

   Economic land-use considerations, modeled in the COL scenario, had a relatively minor impact on system costs and BESS placement decisions. While variations in land costs influenced node-level decisions (e.g., increased reliance on lower-cost areas), the overall system-wide effect was negligible. This finding aligns with stakeholder feedback, which consistently prioritized factors such as permitting delays, grid connectivity, and spatial constraints over land costs in shaping deployment strategies.

   The sensitivity analysis provided by the COL scenario confirms that while land costs may influence specific site-level trade-offs, they are secondary to more pressing considerations such as regulatory barriers and technical feasibility. This highlights the robustness of optimal BESS placement strategies, even under varying economic conditions.

3. **Adaptability of the Dutch HV Grid**

   Despite the constraints imposed by exclusion zones and land-use restrictions, the Dutch HV grid demonstrated remarkable resilience. Congestion levels remained manageable across all scenarios, and the system adapted by redistributing energy flows through alternative nodes and interconnections. For example, even in the 2040 EXCL scenario, system costs increased by only €32.4 million annually—representing a modest rise given the scale of the system.

   This adaptability highlights the inherent flexibility of the HV grid, which can accommodate spatially constrained BESS deployments without compromising operational stability. However, the reliance on alternative flexibility mechanisms, such as HVDC links, introduces new challenges and underscores the importance of strategic planning to minimize cost and dependency.

4. **Increased Reliance on HVDC Connections in Spatially Constrained Scenarios**

   Spatial constraints resulted in an increased reliance on cross-border HVDC interconnections, particularly with the UK. In the 2040 EXCL scenario, electricity imports from the UK increased by 7.56 TWh, necessitating costly HVDC reinforcements. While these interconnections provide a valuable flexibility mechanism, they also represent significant capital expenditures and introduce geopolitical dependencies.

   The findings suggest that HVDC links can effectively complement BESS deployment in spatially constrained scenarios. However, over-reliance on interconnections may undermine energy independence and increase long-term system costs. Policymakers must carefully balance the trade-offs between domestic storage deployment and international energy flows to ensure a resilient and cost-effective grid.

7.3. Implications for Policy and Practice

The findings of this research offer insights that may be useful for policymakers, TSOs, and market actors in addressing challenges and opportunities related to large-scale BESS deployment in the Dutch HV grid. While the results show that short-term priorities exist, the limited impact of suboptimal placement on system costs in 2023 suggests that no immediate, site-specific prioritization is necessary. However, long-term planning must focus on spatial planning, regulatory improvements, and stakeholder alignment to support future BESS deployment and system resilience.

1. **Short-Term Implications: Limited Need for Immediate Intervention**

   The 2023 results suggest that suboptimal BESS placement does not impose significant additional costs or congestion issues. Even in the EXCL scenario, the system adapted through alternative flexibility measures, and cost increases were marginal. This indicates that, in the short term, there is no urgent need for highly specific site prioritization.

   For market actors, this provides flexibility in site selection, allowing practical considerations such as permitting, land availability, and grid connection costs to guide decisions. TSOs and policymakers, meanwhile, can focus on ensuring the overall feasibility of BESS deployment rather than imposing location-specific strategies in the near term.

2. **Long-Term Spatial Planning for BESS Deployment**

   While short-term prioritization is not critical, the 2040 results reveal a significant increase in BESS capacity requirements, with some nodes exceeding 2.9 km^2 of spatial demand. To support these long-term needs, policymakers must take a proactive approach to spatial planning.

   Firstly, this requires identifying and reserving suitable sites. Strategic sites near HV substations and renewable generation hubs should be identified and protected to ensure sufficient land availability for future BESS installations.

   Secondly, spatial constraints such as NATURA2000 zones and urban expansion plans will require careful balancing of energy transition needs with environmental and societal priorities. Strategies such as compensatory measures or alternative zoning policies could help reconcile these conflicts. Finally, given the projected need for approximately 12.3 km^2 of land for 20 GW of BESS capacity in 2040 (in the EXCL scenario), governments must coordinate at national, regional, and local levels to secure long-term spatial resources for energy infrastructure.

3. **Streamlining Permitting Processes**

   Permitting delays emerged as a bottleneck for BESS deployment, highlighting the need for long-term strategies to address regulatory inefficiencies that hinder project timelines. A unified and standardized permitting process across municipalities and regions could reduce uncertainty for developers and accelerate project execution. Additionally, pre-identifying priority zones for energy infrastructure could facilitate faster approvals by minimizing the need for extensive zoning changes or environmental reviews. To achieve this, TSOs, local governments, and national regulators must align their objectives and improve coordination to create a streamlined and supportive regulatory environment for BESS deployment.

4. **Bridging Stakeholder Misalignments**

   A critical barrier to effective BESS deployment lies in the misalignment of priorities among TSOs, market actors, and regional governments as discussed in section 6.1.4. Introducing incentives such as differentiated connection fees or subsidies can encourage system-optimal placement, while regular and transparent communication among TSOs, developers, and policymakers can foster trust and improve alignment of priorities.

5. **Ensuring Long-Term Grid Resilience**

   While the Dutch HV grid has demonstrated adaptability in the short term, ensuring long-term resilience will require strategic and proactive planning. Policymakers and TSOs must develop a national BESS allocation strategy that prioritizes critical stations for deployment based on renewable energy generation, demand growth, and grid requirements. Investments should anticipate future challenges, such as increased renewable penetration and spatial constraints, while ensuring that infrastructure design aligns with projected BESS deployment patterns.

7.4. Evaluation on Learning Process

Reflecting on the learning process during this master thesis study, I can say that this has been one of the most insightful experiences of my study career. Without significant experience in modeling, this experience thought me how to go through the process from problem framing to executing power system models and interpreting results. I learned that a perfect model does not exist and that sufficient time should be calculated in to deepen the understanding of results and process these in a report. Furthermore, I learned how to critically think about the limitations of a model, but not to see these as a shortcoming, but rather as a component inherently related to the complexity of such analyses.

I think this experience has also helped me develop professionally within the environment of TenneT, in which I was able to contribute to interesting projects. Being able to ask for help from such field experts enriched this learning experience even more.

One of my main goals for this thesis was to challenge myself and to contribute meaningfully to the energy transition. I learned that, within this ambition, it is important to remain realistic with regard to the direct impact of results. Sometimes narrower, but deeper research focus leads to more valuable insights. I was surprised with the large amount of result data that came out of the model. Therefore, I had to delineate which elements would be relevant to consider for this study. Next time, I would aim to narrow the scope and size of an energy model to go into a more detailed understanding of the model outcomes.

7.5. Relation to CoSEM

The conclusions of this research highlight key CoSEM themes, including multi-actor decision-making, system complexity, and policy-driven infrastructure planning. The findings show that while technical optimization can identify cost-efficient BESS configurations, real-world implementation is constrained by institutional bottlenecks, land-use conflicts, and economic uncertainties. This shows the importance of integrated decision-making frameworks, where grid operators, policymakers, and market actors must coordinate to balance technical feasibility with spatial and regulatory constraints.

BESS deployment is not solely a technical challenge but a multi-actor coordination problem involving TSOs, regional governments, and market participants. Misalignments between these stakeholders—particularly between TSOs and private BESS developers—create inefficiencies in infrastructure planning. This reflects CoSEM's emphasis on actor complexity, where diverging objectives shape system outcomes. Future research could explore how market mechanisms like connection fees or subsidies might better align private investments with system-wide benefits.

A key CoSEM principle is to look at a system from different perspectives. This study did so by integrating quantitative analysis with real-world actor insights, combining power system optimization modeling with expert interviews from TenneT and BESS developers. The interviews revealed practical barriers—such as permitting delays, regulatory uncertainty, and grid connection constraints—that a purely technical model would overlook. This underscores the importance of mixed-method approaches in ensuring technically optimal solutions are also institutionally feasible.

By applying CoSEM methodologies, this study bridges the gap between technical modeling and strategic decision-making, offering insights for energy system planners and policymakers. It highlights the need for interdisciplinary approaches that integrate engineering, economic feasibility, and governance structures to support a cost-effective, adaptive, and spatially efficient BESS deployment strategy.

7.6. Suggestions for Future Work

This research offers valuable insights into the spatial, economic, and technical considerations for BESS deployment in the Dutch HV grid. However, several areas remain unexplored or require further analysis to provide a more comprehensive understanding of BESS integration into the energy system. Future research should address the following:

1. **Incorporating Other Voltage Levels:**

   The current study focuses exclusively on the 220 kV and 380 kV high-voltage grid. Expanding the analysis to include medium-voltage (MV) and low-voltage (LV) grids could provide a more granular understanding of BESS deployment across different levels of the energy system. This would help capture the interactions between transmission and distribution networks, where smaller-scale storage and flexibility solutions may also play a critical role.

2. **Dynamic Transition Pathways:**

   While this research analyzed two static temporal snapshots (2023 and 2040), future studies could explore dynamic transition pathways between as-is and future scenarios. Modeling intermediate years would allow for better insights into the progressive integration of BESS and the evolution of system costs, capacity needs, and spatial constraints over time.

3. **Stakeholder Market Mechanisms:**

   This research identified misalignments between TSOs, market participants, and regional governments as a significant barrier to effective BESS deployment. Future studies could investigate specific market mechanisms, such as connection fee structures or subsidy schemes, to align stakeholder priorities and incentivize system-optimal placement of BESS. Simulating these mechanisms in a dynamic market context could provide actionable insights for policymakers.

4. **Expanding Storage and Flexibility Types:**

   While this study focused on large-scale lithium-ion BESS, future research could compare the spatial and economic impacts of alternative storage technologies (e.g., flow batteries, compressed air energy storage) and flexibility solutions (e.g., demand-side response, vehicle-to-grid systems). Examining how these alternatives interact with the HV grid and their potential synergies with BESS would provide a more holistic perspective on system flexibility.

5. **Enhanced Spatial Modeling:**

   Incorporating more detailed spatial data, such as land suitability indices and exclusion matrices, would improve the accuracy of future models. For example, factoring in land-use categories beyond exclusion zones, such as marginal agricultural land or industrial zones, could refine site selection criteria and expand the pool of viable BESS locations.

6. **Dynamic Demand Projections:**

   Future models should incorporate adaptive demand scaling that accounts for evolving policy, technology, and market developments. Dynamic projections would better reflect changing energy consumption patterns, electrification trends, and renewable integration, enhancing the robustness of modeling outcomes.

7. **Comparing Zonal and Nodal Market Structures:**

The model used in this research assumes a nodal market structure, which differs from the zonal approach currently employed in many European energy markets. Future studies could analyze how the transition to nodal pricing might impact BESS deployment strategies, system costs, and congestion management, offering insights into the feasibility of such market reforms.

8. **Geographically Accurate Node Placement:**

   The aggregated node locations used in this study may not fully align with real-world substation coordinates. Future research could enhance spatial accuracy by aligning node locations with actual grid infrastructure. This would improve the alignment of exclusion zones with the surrounding land-use realities and provide more realistic insights into spatial constraints.

By addressing these areas, future research can build on the foundations established in this study, advancing the understanding of BESS deployment and integration into spatially constrained energy systems. These efforts will be essential in supporting the continued transition to a resilient, decarbonized electricity grid.

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A

Literature Search

To find academic and peer-reviewed literature for the formulation of a research gap, a backward snowballing method of key theoretical frameworks have been applied and the database Scopus has been used. In Scopus, relevant articles have been obtained by (I) using appropriate key words and Booleans, (II) scoping down on English literature published >2018 and (III) scanning relevancy of the title and the abstract of the research. Here a focus has been laid on literature that examines holistic components next to technological and cost performances of battery energy storage systems.

Table A.1: Methodology for choosing relevant literature on BESS optimization models

Key Words Scopus	**# Hits > 2018**	**Steps**	**Article Chosen**
Battery AND Storage AND {optimal placement}	101	Title scan of top 40 most relevant; → 17 hits left; Abstract scan	-Barla & Sarkar (2023) - Castro & Espinoza-Trejo (2023) - Damian & Wong (2022) - Kazemi & Ansari (2022) - Wong et al. (2019A) - Wong et al. (2019B)
{Open model} AND {Power System}	5	Abstract scan	- Hörsch et al. (2018)
/Power system/ AND /Spatially explicit/	7	Abstract scan and backward snowballing from Lombardi et al. (2020) to Pfenninger and Pickering (2018)	-N. Wang et al. (2020) - Pfenninger and Pickering (2018)
Battery AND Storage AND {transmission system} AND model	107	Title scan of top 40 most relevant → 5 hits left; abstract scan	- Biancardi et al. (2024) - Kijak and Gashi (2024)

Table A.2: Overview of relevant literature

Title	Authors	Date	Journal Source
Optimal placement and sizing of BESS in RES integrated distribution systems.	Barla & Sarkar	2023	International Journal of System Assurance Engineering and Management, 14(5), 1866-1876.
Optimal placement of battery energy storage systems with energy time shift strategy in power networks with high penetration of photovoltaic plants.	Castro & Espinoza-Trejo	2023	Sustainable Energy, Grids and Networks, 35, 101093.
Optimal Energy Storage Placement and Sizing in Distribution System.	Damian & Wong	2022	In 2022 IEEE International Conference in Power Engineering Application (ICPEA) (pp. 1-6).
An integrated transmission expansion planning and battery storage systems placement-A security and reliability perspective.	Kazemi & Ansari	2022	International Journal of Electrical Power & Energy Systems, 134, 107329.
Optimal placement and sizing of battery energy storage system for loss reduction using whale optimization algorithm.	Wong et al.	2019	Journal of Energy Storage, 26, 100892.
Review on the optimal placement, sizing, and control of an energy storage system in the distribution network.	Wong et al.	2019	Journal of Energy Storage, 21, 489-504.
PyPSA-Eur: An open optimization model of the European transmission system	Hörsch et al.	2018	Energy strategy reviews, 22, 207-215.
A spatially explicit planning approach for power systems with a high share of renewable energy sources.	Wang et al.	2020	Applied Energy, 260, 114233
Policy decision support for renewables deployment through spatially explicit practically optimal alternatives	Lombardi et al.	2020	Joule, 4(10), 2185-2207.

Table A.3: Methodology for retrieving relevant literature on spatial planning in energy systems

Key Words Scopus	# Hits > 2018	Steps	Article Chosen
{Location planning} AND Energy AND system	56	Title scan of all; $\rightarrow$ 10 hits left; Abstract scan	- Luo et al. (2023) - Settou et al. (2021) - Wang et al. (2022) - Zhang et al. (2023) - Zhou et al. (2022)
{Power system} AND {Spatially explicit}	7	Abstract scan	- Lombardi et al., 2020
{land use} AND {energy systems}	220	Title scan of first 50; $\rightarrow$ 8 hits left; Abstract scan	- Pedersen et al. (2021) - Hameed et al. (2021)

Table A.4: Overview of relevant literature on spatial planning in energy systems

Title	Authors	Date	Journal Source
Energy Storage Dynamic Configuration of Active Distribution Networks—Joint Planning of Grid Structures.	Luo et al.	2023	Processes, 12(1), 79.
A high-resolution geographic information system-analytical hierarchy process-based method for solar PV power plant site selection: a case study Algeria.	Settou et al.	2021	Clean Technologies and Environmental Policy, 23, 219-234.
Energy Storage Location and Capacity Planning Based on Distribution Network Partition and ResNet DNN.	Wang et al.	2022	2022 5th International Conference on Power and Energy Applications (ICPEA) (pp. 388-392). IEEE.
Optimal Location and Capacity Planning of Distribution Network Considering Demand Response and Battery Storage Capacity Degradation.	Zhang et al.	2023	2023 IEEE 7th Conference on Energy Internet and Energy System Integration (EI2) (pp. 569-575). IEEE.
Energy storage resources management: Planning, operation, and business model.	Zhou et al.	2022	Frontiers of Engineering Management, 9(3), 373-391.
Policy decision support for renewables deployment through spatially explicit practically optimal alternatives	Lombardi et al.	2020	Joule, 4(10), 2185-2207.
Modeling all alternative solutions for highly renewable energy systems	Pedersen et al.	2021	Applied Energy 234, 121294
A business-oriented approach for battery energy storage placement in power systems	Hameed et al	2021	Applied Energy, 298, 117186.

B

Interviews

B.1. Questions Internal interviews

1. How do you perceive the role of BESS in stabilizing the Dutch electricity grid, especially with the increasing share of renewable energy?

Purpose: Understand expert views on the technical benefits of BESS, like stabilizing grid fluctuations.

2. What are the key technical challenges in integrating BESS into the existing Dutch electricity grid infrastructure?

Purpose: Identify grid-specific obstacles such as bandwidth limitations, grid congestion, or technological maturity.

3. Which geographical or spatial constraints do you consider most critical when selecting locations for BESS deployment in the Netherlands?

Purpose: Explore key land-use and environmental restrictions, such as protected zones or urban areas.

4. How do Dutch regulatory frameworks (e.g., PEH for energy storage) influence the planning and placement of BESS installations?

Purpose: Gather perspectives on how regulations shape BESS site selection and what barriers exist due to land-use policies.

5. In your opinion, how do regional variations in ground prices and financial incentives affect the feasibility of BESS placement?

Purpose: Understand the financial impact of location-specific costs, such as land prices and local incentives.

6. What market factors, such as energy prices or grid service revenues, most influence decisions about where to deploy BESS?

Purpose: Identify market-driven factors affecting BESS placement, such as demand response services or energy arbitrage opportunities.

Stakeholder and Socio-technical Considerations: 7. What role do you see for public and private partnerships in facilitating the deployment of BESS across different regions in the Netherlands?

Purpose: Investigate how collaboration between public and private sectors influences BESS projects, especially in financing and implementation.

8. What are the key social or community concerns that need to be addressed when deploying BESS installations near urban or residential areas?

Purpose: Explore potential social resistance or acceptance issues related to large-scale energy storage systems.

9. How do you see the future role of BESS evolving in relation to other energy storage technologies or grid innovations over the next decade?

Purpose: Understand the long-term outlook and potential technological advancements that could impact BESS deployment strategies

B.2. Questions external market interviews

1. What are the primary costs involved in deploying a BESS, from production to being fully operational and connected, and which of these are region-specific? What percentage of the total cost do regional factors represent?
2. How do you account for regional variations, such as permitting, land costs, and grid connections, in planning and placing BESS installations?
3. How do regulatory frameworks and policies influence the planning and placement of BESS installations? Are there any specific regulations that significantly impact regional deployment?
4. Which market factors and financial incentives (e.g., tariffs, ATR 85) have the greatest influence on BESS siting decisions, and are there unintended consequences that need addressing?
5. To what extent have geographical or spatial constraints, such as land availability and zoning restrictions, affected the planning and placement of BESS?
6. How do you see the role of industrial areas versus agricultural lands in hosting BESS installations, and what trade-offs are involved?
7. Which regions in the Netherlands hold the highest potential for BESS deployment, and why? How can coordination between developers and Tennet be improved to align siting with grid needs?

C

Key Variables and Sources

C.1. Key Model Parameters

Table C.1 describes the key model parameters and their respective sources. Although much of this data was available directly from the PyPSA-Eur database, some parameters were sourced externally or coordinated with TenneT.

C.2. Installed capacity assumptions

For the simulations of 2023, historical data was used from a variety of sources. For 2040 on the other hand, some estimations were used from TenneT's scenario quantification. The values that were not identified in the scenarios, were made extendable before the optimization. The values that resulted from the optimization were than fixed (made non-extendable) for other simulations within the same year. Below are the overview tables with the fixed capacities for each country for 2023 and 2040.

Table C.2: Installed Electricity Generation Capacities for Germany (2023 and 2040)(Burger, 2024)TENNET, n.d

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
Germany	Nuclear	0	0
Germany	Off-wind	8500	64 723
Germany	On-wind	58 000	158 878
Germany	Gas	29 600	*244256*
Germany	Coal	36 800	*40791*
Germany	Oil	0	*786*
Germany	Solar PV	66 000	365 875
Germany	Biomass	9000	*8012*

Italicized values are PyPSA model-optimized projections.

Table C.1: Key Fixed Model Parameters and Sources

Parameter	Description	Value	Source
Transmission Lines	Defines the thermal capacity, electrical resistance, and maximum allowable expansion of transmission lines in the network.		PyPSA-Eur database
Wind and Solar Radiation	Provides weather-based capacity factors for wind and solar generation at each node.		Europe-2023-SARAH3-ERA5 (within PyPSA-Eur)
Land Costs	Represents the cost of land per node, influencing financial feasibility in site selection.	Table 4.3	Kadaster (2024)
Demand Profiles	Defines the hourly electricity demand per node based on historical data.		ENTSO-E (within PyPSA-Eur)
Demand Scaling Factor	Adjusts demand projections for future years by applying a multiplier.	2023: False – 2040: 3.0	Netbeheer Nederland, 2023
Expansion Limit	Controls whether new transmission lines can be added to the network.	False	Coordination with TenneT
Marginal Costs for Fossil generators	Defines the cost per MWh of generated electricity and was adjusted via CO_2 prices [€/tonne] to reflect decarbonization policies.	Table 4.7	Coordination with TenneT
CO_2 Budget	Specifies the allowable fraction of 1990-level CO_2 emissions for each modeled year.	2023: False –, 2040: 0%.	Coordination with TenneT
BESS CAPEX Adjustment	Represents the capital expenditures for BESS installation, adjusted for ancillary service income.	2023: CAPEX is reduced by 37.1%, 2040: 0%	TenneT, 2024a, DEA (within PyPSA-Eur)
BESS OPEX	Defines the operational expenses of BESS.	€0/MWh	Coordination with TenneT
Generation Capacity	Provides installed power generation capacity per country and technology type.	Section C.2	Various sources
Opportunity Rate	Represents the assumed opportunity cost rate of land use.	8%.	Coordination with TenneT
Max Hours	Defines the maximum storage duration per BESS installation.	6 hours	Coordination with TenneT
Timestep	Specifies the temporal resolution of the model.	8760 hours (hourly resolution).	Coordination with TenneT
Voltage Levels	Lists the transmission voltage levels included in the model.	220 kV, 300 kV, 380 kV, and 400 kV.	Coordination with TenneT

Table C.3: Installed Electricity Generation Capacities for the Netherlands (2023 and 2040)

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
Netherlands	Nuclear	482	1500
Netherlands	Off-wind	5269	41 500
Netherlands	On-wind	4500	15 100
Netherlands	Gas	20 000	*11734*
Netherlands	Coal	3500	*6901*
Netherlands	Oil	500	*0*
Netherlands	Solar PV	15 000	122 700
Netherlands	Biomass	2000	*220*

Italicized values are PyPSA model-optimized projections.

Table C.4: Installed Electricity Generation Capacities for Belgium (2023 and 2040)

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
Belgium	Nuclear	3908	0
Belgium	Off-wind	2263	6560
Belgium	On-wind	2500	7505
Belgium	Gas	6000	*18412*
Belgium	Coal	1800	*0*
Belgium	Oil	1000	*127*
Belgium	Solar PV	5000	26 285
Belgium	Biomass	800	*6251*

Italicized values are PyPSA model-optimized projections.

Table C.5: Installed Electricity Generation Capacities for Norway (2023 and 2040)

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
Norway	Nuclear	0	0
Norway	Off-wind	96	2000
Norway	On-wind	5073	2425
Norway	Gas	0	*0*
Norway	Coal	0	*0*
Norway	Oil	0	*0*
Norway	Solar PV	299	2500
Norway	Biomass/thermal	642	*0*
Norway	Hydro	34 139	37 400

Italicized values are PyPSA model-optimized projections.

Table C.6: Installed Electricity Generation Capacities for Denmark (2023 and 2040)

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
Denmark	Nuclear	0	0
Denmark	Off-wind	2343	10 722
Denmark	On-wind	6100	4925
Denmark	Gas	1500	*2668*
Denmark	Coal	1000	*3084*
Denmark	Oil	500	*0*
Denmark	Solar PV	2500	36 419
Denmark	Biomass	1000	*5365*

Italicized values are PyPSA model-optimized projections.

Table C.7: Installed Electricity Generation Capacities for the UK (2023 and 2040)

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
UK	Nuclear	5883	13 236
UK	Off-wind	14 741	95 158
UK	On-wind	14 000	42 040
UK	Gas	30 000	*61131*
UK	Coal	1000	*5834*
UK	Oil	500	*0*
UK	Solar PV	14 000	59 287
UK	Biomass	3000	*21644*

Italicized values are PyPSA model-optimized projections.

Table C.8: Installed Electricity Generation Capacities for Ireland (2023 and 2040)

Country	Generator Type	2023 Capacity [MW]	2040 Capacity [MW]
Ireland	Nuclear	0	0
Ireland	Off-wind	200	11 096
Ireland	On-wind	4100	9686
Ireland	Gas	4652	*4389*
Ireland	Coal	855	*1096*
Ireland	Oil	292	*208*
Ireland	Solar PV	720	13 162
Ireland	Biomass	42	*68*

Italicized values are PyPSA model-optimized projections.

C.3. CORINE Exclusion Codes

For the exclusion of land, the excludability matrix of Solar-PV was used. The following CORINE codes were used as exclusion areas [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 26, 31, 32]. An overview of each category and its description is given in table C.9

Table C.9: CORINE codes

Code	Category	Description
1	Artificial surfaces	General category for built-up and man-made areas.
2	Agricultural areas	General category for farming, cultivation, and managed land.
3	Forest and semi-natural areas	Includes forests, scrub, and other natural vegetation.
4	Wetlands	Areas permanently or seasonally saturated with water.
5	Water bodies	Natural or artificial water areas such as rivers, lakes, and reservoirs.
6	Continuous urban fabric	High-density urban areas with very few open spaces.
7	Discontinuous urban fabric	Low-density urban areas with significant green or open spaces.
8	Industrial or commercial units	Industrial zones, warehouses, and commercial spaces.
9	Road and rail networks	Transport infrastructure such as roads, railways, and associated structures.

10	Port areas	Coastal or inland port areas.
11	Airports	Land used for airports, including runways and terminal zones.
12	Mineral extraction sites	Areas of quarries, mines, and other mineral extraction activities.
13	Dump sites	Landfills and waste disposal areas.
14	Construction sites	Areas under development or construction.
15	Green urban areas	Parks, gardens, and recreational green spaces in urban settings.
16	Sports and leisure facilities	Sports fields, golf courses, and other outdoor recreational facilities.
17	Non-irrigated arable land	Dry-farmed fields without irrigation.
18	Permanently irrigated land	Cultivated areas that are consistently irrigated.
19	Rice fields	Areas specifically used for cultivating rice.
20	Vineyards	Land covered with grapevines for wine production.
26	Transitional woodland-shrub	Areas transitioning between forest and shrubland, often due to degradation.
31	Inland wetlands	Wetlands away from the coastline, such as marshes and bogs.
32	Coastal wetlands	Wetlands near the sea, including salt marshes and intertidal zones.

D

Additional Analyses and Results

Some additional analyses were performed that did not add directly to answering the research questions guiding this study. Nevertheless, they can add to the understanding and context of the results or function as a base for future research.

D.1. Results

This section outlines some of the tables that add more depth to the results presented in Chapter 5. They are presented here to ensure readability in the document.

D.1.1. BESS allocation

The tables below represent the spatial requirements at each node for the allocated BESS capacity across the three scenarios.

Table D.1: Spatial requirements for BESS 2023 across scenarios

Bus	Base [ha]	COL [ha]	EXCL [ha]
NL0 0	7.4	7.2	7.4
NL0 1	7.7	5.9	17.1
NL0 2	15.8	15.7	0.0
NL0 3	0.0	0.0	0.0
NL0 4	4.5	4.6	0.0
NL0 5	0.0	0.0	0.0
NL0 6	6.2	5.5	0.0
NL0 7	3.8	3.0	5.7
NL0 8	1.9	0.0	11.3
NL0 9	0.0	0.0	13.6
NL0 10	0.0	0.0	0.0
NL0 11	18.0	18.1	0.0
NL0 12	7.1	6.7	0.0
NL0 13	12.2	9.7	0.0
NL0 14	6.1	6.0	0.0
NL0 15	0.0	0.0	0.0
NL0 16	0.0	0.0	0.0
NL0 17	6.3	6.0	0.0
Total	**97.1**	**88.4**	**55.0**

Table D.2: Spatial requirements for BESS 2040 across scenarios

Bus	Base [ha]	COL [ha]	EXCL [ha]
NL0 0	131.8	130.1	248.1
NL0 1	109.5	92.4	237.8
NL0 2	44.3	41.2	0.0
NL0 3	132.5	126.3	0.0
NL0 4	158.4	154.5	0.0
NL0 5	10.5	6.9	0.0
NL0 6	0.0	0.0	0.0
NL0 7	185.6	183.3	262.7
NL0 8	2.7	8.6	286.8
NL0 9	2.6	3.3	87.8
NL0 10	61.4	39.5	107.9
NL0 11	195.6	198.7	0.0
NL0 12	77.4	70.7	0.0
NL0 13	29.5	23.5	0.0
NL0 14	90.8	86.7	0.0
NL0 15	0.0	0.0	0.0
NL0 16	145.6	140.3	0.0
NL0 17	140.3	146.3	0.0
Total	**1.518.6**	**1,452.3**	**1,231.1**

D.1.2. Congestion and Line Utilization

These tables present the line capacities underlying the grid congestion figures. For each line, its maximum capacity (in MW) is given, alongside its line loading and peak load frequency (in %) for each scenario.

Table D.3: Line Metrics for 2023

Line nr.	Bus0	Bus1	Max Cap (MW)	LL% (B)	LL% (C)	LL% (E)	PL% (B)	PL% (C)	PL% (E)
22	NL0 0	NL0 16	4349	53.1	53.1	53.1	10.0	10.1	10.5
23	NL0 0	NL0 17	5039	49.1	49.1	49.2	10.4	10.3	10.7
24	NL0 1	NL0 11	1514	36.7	36.6	32.9	6.0	5.8	1.9
25	NL0 1	NL0 15	4028	52.2	52.2	51.4	3.0	3.0	2.8
26	NL0 1	NL0 5	1850	61.7	61.6	62.1	9.5	9.4	9.7
27	NL0 10	NL0 11	2018	40.8	40.7	39.6	8.4	8.4	7.1
28	NL0 10	NL0 17	4599	45.6	45.5	45.5	9.9	9.8	10.0
29	NL0 10	NL0 17	4599	45.6	45.5	45.5	9.9	9.8	10.0
30	NL0 10	NL0 5	7650	55.7	55.5	55.1	7.1	6.8	6.5
31	NL0 12	NL0 6	6166	59.6	59.6	59.1	25.4	25.2	24.2
32	NL0 12	NL0 8	6934	58.5	58.5	57.9	24.7	24.6	23.1
33	NL0 13	NL0 2	4560	50.8	50.7	48.2	6.0	5.8	4.0
34	NL0 13	NL0 9	3396	75.3	75.3	74.6	15.7	15.6	15.2
35	NL0 14	NL0 2	4088	61.6	61.5	60.8	28.8	28.7	27.3
36	NL0 14	NL0 6	4571	59.4	59.4	58.7	27.2	27.0	25.8
37	NL0 15	NL0 5	5565	62.6	62.6	63.0	10.4	10.4	10.9
38	NL0 16	NL0 4	5170	64.7	64.7	64.4	26.0	26.1	25.8
39	NL0 16	NL0 7	4488	48.2	48.2	48.3	10.2	10.3	10.7
40	NL0 16	NL0 8	6792	36.9	36.9	37.0	0.0	0.0	0.1
41	NL0 17	NL0 7	3698	53.8	53.7	54.2	10.3	10.2	10.3
42	NL0 3	NL0 8	6971	60.6	60.6	60.6	32.0	31.8	31.6
43	NL0 4	NL0 8	3396	52.0	52.0	51.1	9.9	9.8	9.3
44	NL0 5	NL0 9	9085	64.3	64.3	64.3	33.8	34.0	33.8
Average	-	-	-	**54.3**	**54.2**	**53.5**	**13.5**	**13.4**	**12.8**

Notes:
* LL stands for Average Line Loading, PL stands for Frequency Peak Loading.
** The subscript letters B, C, and E indicate the scenario's Base, COL, and EXCL.

D.1.3. Line Metrics for 2040

Table D.4: Line Metrics for 2040

Line nr.	Bus0	Bus1	Max Cap (MW)	LL%* (B)**	LL% (C)	LL% (E)	PL% (B)	PL% (C)	PL% (E)
22	NL0 0	NL0 16	12408	42.4	42.3	38.7	2.2	2.2	0.9
23	NL0 0	NL0 17	13104	38.4	38.3	37.6	0.7	1.0	0.9
24	NL0 1	NL0 11	4847	29.8	29.9	22.8	0.7	0.7	0.1
25	NL0 1	NL0 15	10738	18.3	18.2	19.0	0.4	0.4	0.4
26	NL0 1	NL0 5	3268	50.1	50.2	51.7	3.0	2.9	4.1
27	NL0 10	NL0 11	4390	41.2	41.3	35.8	6.1	5.5	2.6
28	NL0 10	NL0 17	13725	32.9	33.0	31.6	1.0	0.5	0.8
29	NL0 10	NL0 17	13725	32.9	33.0	31.6	1.2	1.2	1.0
30	NL0 10	NL0 5	24379	37.3	36.8	35.2	0.7	0.5	0.3
31	NL0 12	NL0 6	21329	45.4	44.9	44.0	0.7	0.7	0.3
32	NL0 12	NL0 8	18826	57.8	57.6	57.1	9.4	9.2	9.1
33	NL0 13	NL0 2	12981	22.6	22.5	18.2	0.2	0.2	0.1
34	NL0 13	NL0 9	5219	66.6	66.7	61.8	15.7	15.9	9.5
35	NL0 14	NL0 2	9748	35.7	35.6	30.7	0.4	0.4	0.2
36	NL0 14	NL0 6	8275	51.4	52.1	53.7	3.1	3.2	5.0
37	NL0 15	NL0 5	9627	46.1	46.2	47.5	1.9	1.8	1.7
38	NL0 16	NL0 4	19110	61.4	61.6	57.0	2.6	2.5	0.1
39	NL0 16	NL0 7	10514	43.2	43.1	40.5	2.4	2.4	1.1
40	NL0 16	NL0 8	6792	46.2	45.3	54.5	16.1	15.6	23.0
41	NL0 17	NL0 7	12526	35.2	35.2	33.4	1.3	1.3	0.7
42	NL0 3	NL0 8	10947	66.9	66.5	70.6	35.2	34.6	40.4
43	NL0 4	NL0 8	10792	65.4	66.0	62.4	15.9	16.9	7.7
44	NL0 5	NL0 9	14963	70.0	69.4	67.2	3.8	2.8	2.1
Average	-	-	-	**44.9**	**44.9**	**43.8**	**5.9**	**5.8**	**5.7**

Notes:
* LL stands for Average Line Loading, PL stands for Frequency Peak Loading.
** The subscript letters B, C, and E indicate the scenario's Base, COL, and EXCL.

D.1.4. Import and Export

Although the international power flows did not change significantly, the results for this analysis are displayed below.

Table D.5: cross-country Import/export balance data 2023

From	To	I/o bl* Base [TWh/year]	I/o bl COL [TWh/year]	I/o* bl EXCL [TWh/year]
NO	GB	7.11	7.11	7.10
GB	NL	7.29	7.28	6.96
GB	DK	7.17	7.17	7.19
DK	NO	9.48	9.48	9.48
NO	DE	49.72	49.72	49.72
DE	DK	2.36	2.36	2.37
IE	GB	4.01	4.01	4.02
NL	DK	6.07	6.06	6.06
GB	BE	16.41	16.40	16.17
DE	BE	3.72	3.72	3.75
NO	NL	54.38	54.38	54.38

* I/o bl stands for import/export balance

Table D.6: Cross-country import/export balance data 2040

From	To	I/o* bl Base [TWh/year]	I/o bl COL [TWh/year]	I/o bl EXCL [TWh/year]
GB	NL	**32.9**	**32.1**	**39.7**
GB	DK	4.7	4.67	4.89
DK	NO	146.3	147.5	147.5
GB	NO	90.7	90.7	90.7
NO	DE	40	40	40.1
DE	DK	0.6	0.7	0.7
IE	GB	2.5	2.5	2.4
NL	DK	4.8	4.8	4.7
GB	BE	**7.4**	**8.5**	**0.8**
BE	DE	**4.8**	**4.1**	**0**
DE	BE	**0**	**0**	**4.7**
NO	NL	58.1	58.1	58.1

* I/o bl stands for import/export balance

D.2. Congestion and line load analysis N-1

In an attempt to take into account N-1 principles in the congestion analysis the figures that were created for this purpose were altered slightly. Namely, instead of assuming a maximum of 100% peak load on a transmission line, this percentage was lowered to 90%. The following graphs D.1 and D.2 resulted from this analysis.

D.3. Regional differences in Dutch BESS deployment

Regulatory Data

Spatial regulations governing land use and development, such as zoning restrictions and environmental protections, were not directly integrated into the optimization model due to the limited availability of information on regional restrictions. Interviews TenneT 1 and Market 1 highlighted that this gap stems from a ”chicken-and-egg” problem, where policymakers are waiting for TSOs to provide research and advice on optimal BESS placement, while TSOs, in turn, rely on clear regulatory frameworks to guide their planning. As a result, there is currently no comprehensive regulation defining specific regional restrictions or installation zones for BESS deployment. This lack of clarity makes it challenging to translate potential regulatory constraints into actionable model inputs. While national frameworks like the PEH (RVO, 2024a) offer general guidance, they do not provide the granular details necessary to align BESS optimization models with local land-use policies. This study, therefore, prioritized generalizable insights into the impacts of spatial constraints and economic considerations on BESS placement, while acknowledging the need for future research to address this regulatory void and develop models that incorporate evolving policy directives. Nevertheless, the implications of existing regional reports on BESS placement were qualitatively analyzed and are summarized in table D.8.

In the Netherlands, the 1998 Energy law rules the decision-making and separation between provincial authority and national authority (Repowered & APPM, 2023). For large projects, the national government (Rijksoverheid) may intervene, especially if they are deemed of national importance. In such cases, the Rijkscoördinatieregeling (RCR) may be applied. This arrangement allows the national government to coordinate the permitting process. However, TenneT experts [Interview 1; Interview 3] highlight a dynamic wherein local policymakers must thoroughly understand the complexities of large-scale battery system placement before formulating regulations. At the same time, they rely on grid operators for guidance, although neither party possesses comprehensive knowledge on the matter. Table D.7 represents the separation between regional- and national government authorities.

Several provinces outsourced consultancy projects on the topic of BESS placement. Table D.8 details the reports’ relevant outcomes. Interestingly, only three (out of 12) provinces have made efforts to research this topic in anticipation of the upcoming BESS capacity allocation.

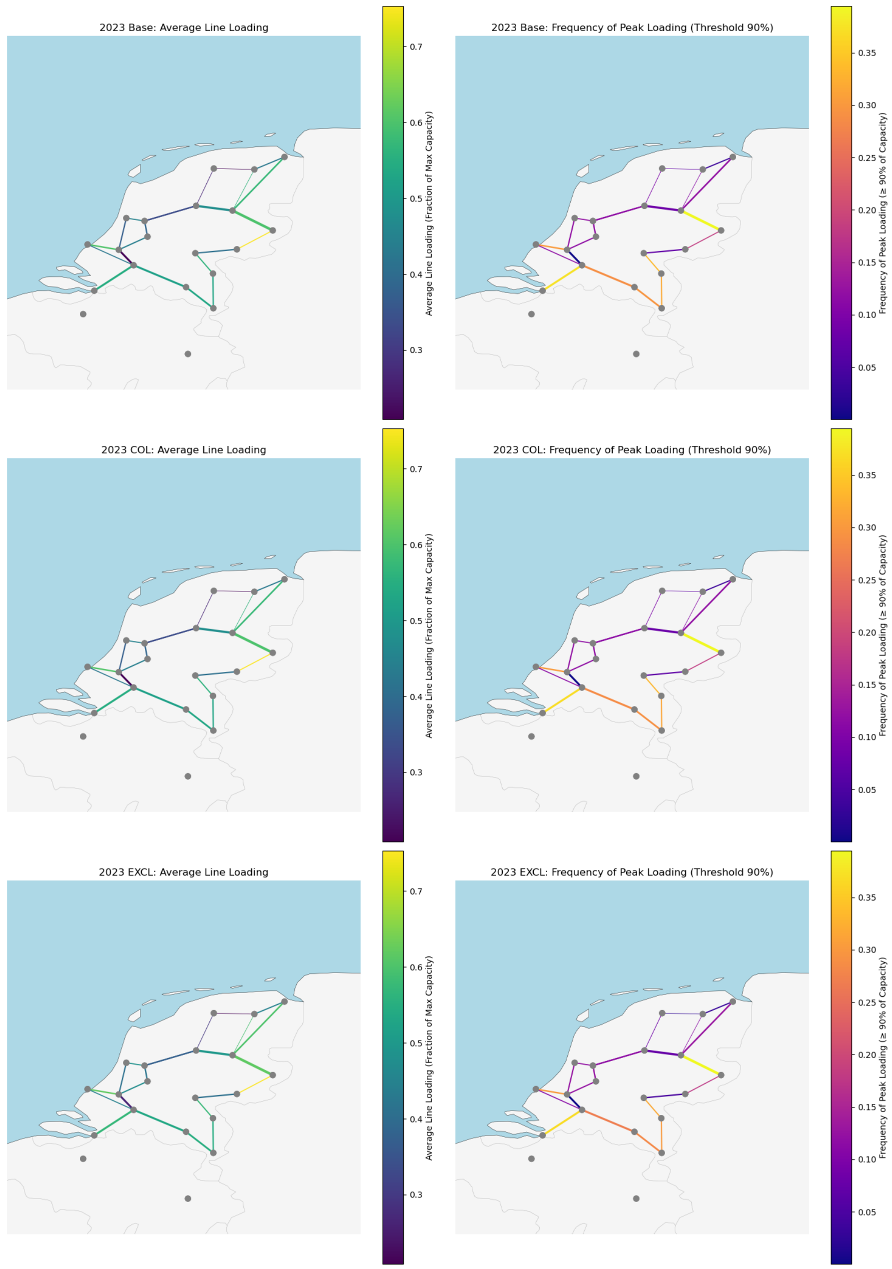

Figure D.1: Line loading and peak frequency under 90% peak capacity limitation 2023

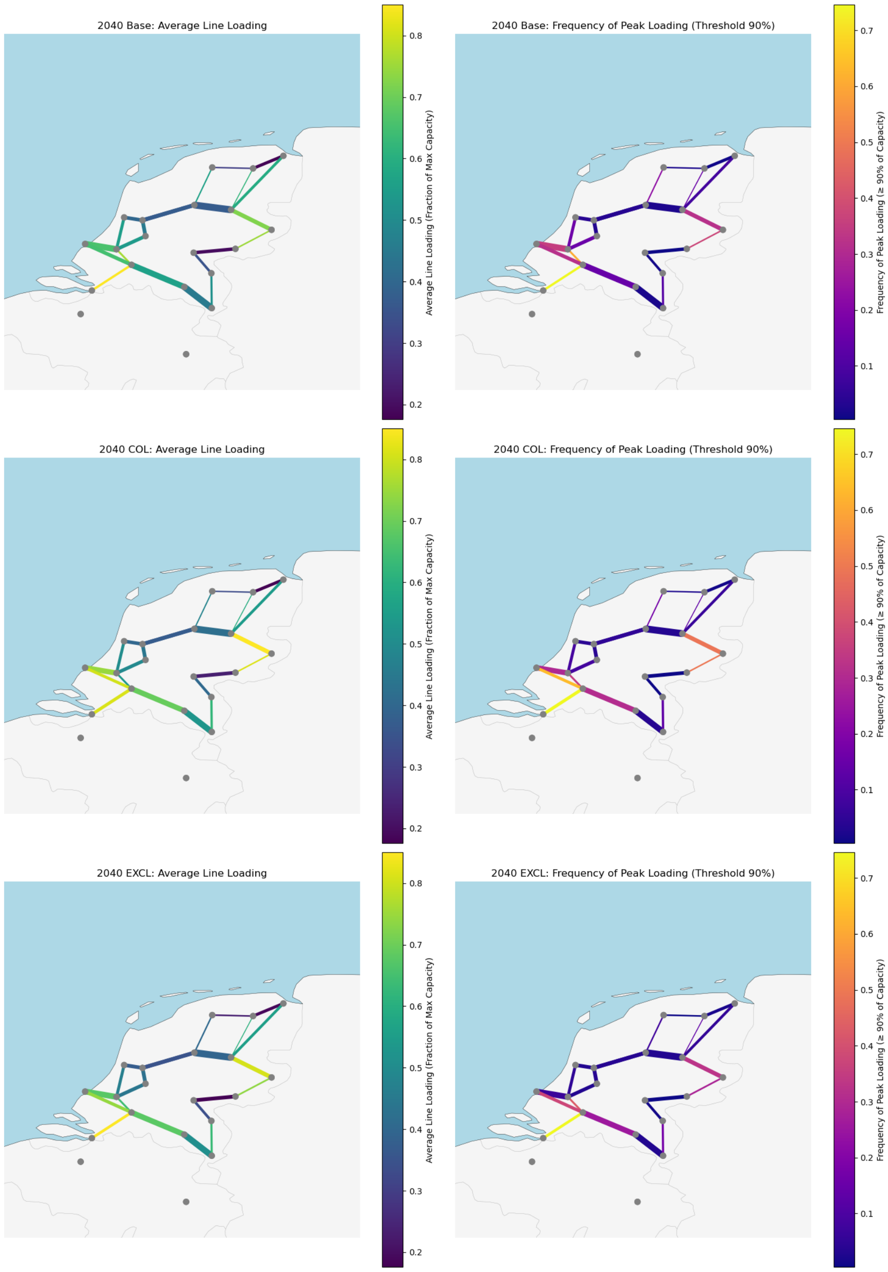

Figure D.2: Line loading and peak frequency under 90% peak capacity limitation 2040

Table D.7: Overview of the authority distribution between the national and provincial governments under the Electricity Act 1998

Construction and expansion of a production installation for generating	Using	Location	Capacity	Authority
Renewable electricity	Wind energy	On land	>100 MW	National government
	Other than wind energy	-	>50 MW	National government
	-	-	>50 - <100 MW	Provincial government
Non-renewable electricity	-	-	>500 MW	National government
	-	-	Expansion up to at least 500 MW	National government

Table D.8: Overview of provincial regulation on technology, safety, environment, and climate

Province	Technical	Safety	Climate	Environment	Source
Drenthe	No standard assessment is conducted by the municipality regarding the impact of the electricity storage system on the electricity grid, as this falls under the authority of the grid operator.	Currently, there are three situations where the PGS 37-1 (Publication Series on Hazardous Substances) can be declared applicable.		(1) In the case of large-scale battery storage systems, at least 10% of the total area must be used for landscape integration. (2) Secondly, criteria can be set for the quality and content of the deployment plan.	Karsens et al., 2024

Province	Technical	Safety	Climate	Environment	Source
Flevoland	- Maximum of 2GW in 2030 - Within 1000 meters of a high-voltage substation, but not directly in line with a rail (to allow for potential future station expansions). - It is expected that the battery capacity will range from 70 MW to approximately 250 MW. - The batteries should be distributed evenly across the province and along the high-voltage corridors.	Regarding health, the main focus is on the aspect of Low-Frequency Noise (LFG). Noise might be of harmful impact if BESS is placed too close to residential areas.	At present, battery storage as an environmentally impactful activity (EOS = energy storage system) has not been designated. This is expected to be addressed by mid-2025.	Many generation locations are situated in the rural areas of Flevoland.	RND, 2024 Flevoland, 2024
Groningen	No standard assessment is conducted by the municipality regarding the impact of the electricity storage system on the electricity grid, as this falls under the authority of the grid operator.	The draft guideline PGS-37-1 outlines the key measures and safety aspects for Energy Storage Systems (EOS).		* Eemshaven * Meeden * Vierverlaten/-Groningen	Repowered and APPM, 2023
Utrecht	There is no standardized test for measuring system-wide effects of BESS. This responsibility lies with the TSO's and DSO's				RVO, 2024b
Overijssel	*No information available*				
Noord-Holland	*No information available*				
Zeeland	*No information available*				
Zuid-Holland	*No information available*				
Friesland	*No information available*				
Gelderland	*No information available*				
Limburg	*No information available*				
Noord-Brabant	*No information available*				

D.4. Safety

The regional analysis described in the section above pointed out that several safety measures should be considered when placing BESS, especially the PGS-37-1 framework.

The PGS 37-1 specifically applies to electricity storage systems consisting of lithium-containing rechargeable energy carriers that are electrically interconnected (in groups) with a total installed capacity exceeding 20 kWh. The primary hazard associated with the use of lithium-containing energy carriers is the potential occurrence of a so-called thermal runaway. This occurs when a battery or other energy storage system generates heat faster than it can dissipate, leading to a rapid and uncontrollable increase in temperature. This can cause further reactions, releasing more heat and potentially resulting in fire, explosion, or system failure. It's a critical safety concern, particularly in lithium-ion batteries, often triggered by overcharging, physical damage, or internal short circuits.

This PGS framework applies to electricity storage systems, including peripheral equipment and the Battery Management System (BMS), starting from the moment the electricity storage system is put into operation. Several types of electricity storage systems are distinguished, such as standalone electricity storage systems, energy storage parks, or mobile electricity storage systems.

The location and manner in which an electricity storage system is used do not affect the applicability of the PGS. The PGS 37-1 outlines preventive and corrective measures that must be taken for each type of electricity storage system. By implementing these measures, the objectives described in the PGS, such as ensuring the safe shutdown of the BESS in case of emergencies, are achieved.

The PGS reflects the state of the art. As such, a newer edition of a PGS guideline may contain updated or stricter measures. These measures must be implemented by the party responsible for the activity. However, for existing situations, it may be unreasonable to require immediate compliance with new measures. Therefore, the PGS guideline includes an implementation period for existing situations.

In TenneT's position paper, they highlight an additional safety measure where BESS developers must place at least 100 meters from station boundaries (TenneT, 2024d)

D.5. Spatial Station Data

This research did not match nodes to real-world station coordinates. However, these coordinates were retrieved in an attempt to include them in the model. They might serve for future research and are provided in the table below.

Full Name	**Debrevation**	**Type**	**Location**	**Longitude**	**Latitude**	**Space?**
Almere 380	ALM380	380kV	Lelystad	5.34377	52.40313	No restriction
Station Breukelen Kortrijk 380	BKK380	380kV	Stichtse Vecht	4.98756	52.16055	No restriction
Station Boxmeer 380	BMR380	380kV	Boxmeer	5.91302	51.63854	No restriction
Station Borssele 380	BSL380	380kV	Borsele	3.72834	51.43358	No restriction
Station Beverwijk 380	BVW380	380kV	Beverwijk	4.67931	52.47287	No restriction
Station Bleiswijk 380	BWK380	380kV	Lansingerland	4.53038	52.03622	No restriction
Compensatie en Filterstation Eemshaven 380kV	CFE380	380kV	Eemsmond	6.86805	53.43676	No restriction
Station Crayestein 380	CST380	380kV	Dordrecht	4.74796	51.81375	No restriction
Station Diemen 380	DIM380	380kV	Diemen	5.01482	52.33668	Restricted Space
Station Doetinchem 380	DTC380	380kV	Bronckhorst	6.25184	51.98196	No restriction
Station Eemshaven 380	EEM380	380kV	Eemsmond	6.87392	53.42517	No restriction
Station Eindhoven 380	EHV380	380kV	Eindhoven	5.53253	51.44682	No restriction

Full Name	Debrevation	Type	Location	Longitude	Latitude	Space?
Station Ens 380	ENS380	380kV	Noordoostpolder	5.80862	52.61681	No restriction
Station Hoek van Holland 380	HVH380	380kV	Rotterdam	4.16271	51.95941	No restriction
Station Krimpen a/d IJssel 380	KIJ380	380kV	Krimpen a/d IJssel	4.63067	51.91447	No restriction
Station Lelystad 380	LLS380	380kV	Lelystad	5.53886	52.57655	No restriction
Station Meeden 380	MEE380	380kV	Midden-Groningen	6.94956	53.12352	No restriction
Station Oostzaan 380	OZN380	380kV	Oostzaan	4.87618	52.42896	No restriction
Station Rilland 380	RLL380	380kV	Reimerswaal	4.21872	51.42386	No restriction
Station Simonshaven 380	SMH380	380kV	Nissewaard	4.26595	51.83935	No restriction
Station Vierverlaten 380	VVL380	380kV	Groningen	6.47451	53.21347	No restriction
Station Wijchen 380	WCN380	380kV	Wijchen	5.71621	51.82134	No restriction
Station Westerlee 380	WL380	380kV	Westland	4.22403	51.98252	Restricted Space
Station Dodewaard 380	DOD380	380kV	Neder-Betuwe	5.66401	51.92690	No constraints
Eemshaven Converterstation 380	EDC380	380kV	Eemsmond	6.86627	53.43463	No constraints
Station Eemshaven Synergieweg 380	EHS380	380kV	Eemsmond	6.86042	53.43987	Limited space
Station Eemshaven Temporary 380	EMT380	380kV	Eemsmond	6.87515	53.42517	No constraints
Station Eemshaven Oudeschip 380	EOS380	380kV	Eemsmond	6.86239	53.43596	No constraints
Maasvlakte-Amaliahaven 380	MAH380	380kV	Rotterdam	4.01196	51.95082	No constraints
Middenmeer 380	MDM380	380kV	Hollands Kroon	5.03472	52.79014	No constraints
Station Maasbracht 380	MBT380	380kV	Maasgouw	5.91852	51.14844	No constraints
Station Maasvlakte 380	MVL380	380kV	Rotterdam	4.02262	51.95559	No constraints
Ter Apelkanaal 380	TAK380	380kV	Westerwolde	7.03944	52.92779	No constraints
Tilburg 380 hline Veenoord Boerdijk 380	TLB380 VBO380	380kV 380kV	Tilburg Emmen	5.06522 6.83509	51.60554 52.73184	No constraints No constraints
Waddenweg Converterstation 380	WDC380	380kV	Eemsmond	6.86709	53.43559	No constraints
Station Wateringen 380	WTR380	380kV	Westland	4.30687	52.01572	Restricted Space
Station Zwolle 380	ZL380	380kV	Zwolle	6.19003	52.52989	No restriction
Station Bergum 220	BGM220	220kV	Tytsjerksteradiel	6.02813	53.21216	No restriction

Full Name	Debrevation	Type	Location	Longitude	Latitude	Space?
Station Delesto 220	DES220	220kV	Delfzijl	6.95406	53.31800	No restriction
Station Ens 220	ENS220	220kV	Noordoostpolder	5.81068	52.61739	No restriction
Station Hessenweg 220	HSW220	220kV	Zwolle	6.18821	52.53108	No restriction
Station Meeden 220	MEE220	220kV	Midden-Groningen	6.94608	53.12450	No restriction
Station Zeyerveen 220	ZYV220	220kV	Assen	6.52402	53.00972	No restriction