Congestion-Neutral Operation of Residential Battery Storage in the Dutch Electricity Grid

Modelling Grid Impact and Economic Feasibility for Aggregator-Controlled R-BESS

Thesis report

by

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to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on September 8, 2025 at 14:30

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

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Preface

Presented here is my master thesis, “Congestion-Neutral Operation of Residential Battery Storage in the Dutch Electricity Grid: Modelling Grid Impact and Economic Feasibility for Aggregator-Controlled R-BESS.” This thesis marks the final milestone in my MSc studies in Complex Systems Engineering and Management at Delft University of Technology.

The motivation for this thesis stems from my deep desire to contribute meaningfully to the transition towards a sustainable energy system. In particular now, in a time when climate change often appears to slip lower on political agendas, I felt an even stronger responsibility and motivation to explore solutions that can help address our pressing energy challenges.

This thesis was carried out during an internship at Witteveen+Bos, alongside my studies at TU Delft. The journey of conducting this research was both enriching and challenging. After spending half a year studying abroad in Japan, I returned full of energy, only to face an unexpected setback in the very first week of my thesis work: a knee fracture that temporarily limited my mobility. This period of immobility proved to be mentally demanding, as it coincided with the start of an intense and complex modelling process that tested both my resilience and analytical abilities. I would like to sincerely thank my supervisors from TU Delft and Witteveen+Bos for their flexibility and support during this time.

I am deeply grateful for the guidance and support received during this journey. Firstly, I would like to thank Francesco Lombardi, my first supervisor at TU Delft, whose biweekly meetings provided invaluable modelling insights and helped sharpen my analytical approach. My second supervisor, Ron van Duin, offered essential perspectives on structuring my thesis, ensuring clarity and coherence throughout my work. Additionally, I extend my thanks to Ivo Bouwmans, my committee chair, whose encouraging guidance consistently helped me put setbacks into perspective.

I would also like to express my sincere appreciation to my supervisor at Witteveen+Bos, Niels Janssen, for the weekly guidance, critical feedback, and insightful questioning that continuously prompted me to reflect on the contribution of each step toward answering my research questions. Casper Berkhout, my colleague at Witteveen+Bos, deserves special recognition for stepping in with crucial modelling support whenever I faced technical obstacles.

The conversations with industry actors, including Alliander, Liander, Zonneplan, CE Delft, and Essent, provided valuable practical insights and enriched the depth of my research. I am sincerely grateful to each organization and their representatives for generously sharing their time and expertise.

On a more personal note, I would like to thank my friends and family for their support and encouragement throughout this process. Their presence helped me maintain a healthy balance between my research and personal life, which I initially underestimated. Looking back, I now realize how easy it is to become fully absorbed in a topic that truly captures your interest.

Finally, this thesis journey taught me that complex problems require structured, step-by-step approaches. Challenges that unfold over several months cannot be addressed effectively without careful planning and clearly defined objectives. Throughout the process, I also came to understand the importance of collaboration. Addressing the energy transition requires input from a wide range of actors, and working with experts across the sector showed me how essential shared knowledge and cooperation are to finding effective solutions. This project deepened my understanding of energy systems, particularly in relation to the integration of residential battery storage. It allowed me to explore both the technical and economic aspects of battery operation and highlighted the importance of smart coordination in reducing grid congestion.

In addition, the experience strengthened my interest in working with complex systems. I discovered how much I enjoy breaking down multifaceted challenges and translating them into clear, actionable recommendations that can support decision-making in practice.

Tanne Heemsbergen
Delft, August 2025

Summary

The ongoing electrification of the Dutch energy system, driven by ambitious 2050 climate targets, is causing increasing congestion in medium- and low-voltage electricity networks. A key challenge lies in the mismatch between rapidly increasing renewable electricity generation and the limited capacity of the grid infrastructure. This imbalance not only delays the energy transition but also obstructs economic growth, as businesses and consumers struggle to connect new renewable projects to the grid. Residential Battery Energy Storage Systems (R-BESS) are considered a key flexibility solution to mitigate this problem. However, if operated purely for market profit, especially through arbitrage and participation in the imbalance market, R-BESS can unintentionally exacerbate grid congestion. This thesis investigates how congestion-neutral operation of R-BESS can be implemented to ensure their contribution to a stable and resilient grid.

This thesis investigates how the concept of congestion-neutral operation, a relatively new design approach that aims to prevent residential batteries from contributing to peak grid load, can be applied to the integration of R-BESS. While R-BESS are often deployed to maximize economic returns through market participation, this research focuses on the impact of this implementation and investigates operational strategies that explicitly avoid increasing grid congestion.

The central research question addressed is: *How can congestion-neutral R-BESS be integrated into Dutch electricity networks to mitigate net congestion while balancing techno-economic trade-offs?*

A mixed-method approach was applied. The qualitative phase involved literature review and interviews with involved actors (distribution system operators, aggregators, and policy advisors) to identify key technical and institutional design elements for congestion-neutral R-BESS. The quantitative phase implemented a Mixed-Integer Linear Programming model in PyPSA to simulate R-BESS behavior at aggregator level under various market scenarios. The model was applied to a real Dutch medium-voltage substation (MSR), with scenario analyses for 2024 and 2030, supported by sensitivity and robustness testing on weather variability and system parameters.

Results show that uncoordinated R-BESS operation substantially increases congestion, particularly in the imbalance market. The outcomes are summarized in Table 1. Congestion-neutral strategies, in particular time constraints, significantly reduced negative grid impacts. For example, applying time constraints reduced new congestion events by half for day-ahead and imbalance 2024 scenarios. However, mitigation periods also decreased with more than 25% for both scenarios. In addition, time-constraint operation preserved economic viability in the day-ahead market: total system costs increased by only 0.9% (2024) and 1.3% (2030), when combining battery trading with self-consumption ("value stacking"). However, for the imbalance market, total system costs increased by 3.47% and 5.09% under time-constraint operation.

The study highlights key trade-offs between grid impact and business model profitability. It also identifies limitations, including single-node focus and perfect foresight assumptions.

Practical recommendations include enabling congestion-neutral R-BESS through flexible constraints, distinguishing day-ahead and imbalance market, and clear coordination between DSOs and aggregators. Future research should extend to multinode grids, explore dynamic real-time signals, and further integrate market design for congestion-neutral flexibility services.

All results of this thesis are open source. The complete model developed for this research is publicly available at:

https://github.com/Tanneheemsbergen/pypsa-NL2025

Table 1: Overview of model scenarios including mitigation events and costs. DA = Day-ahead, IMB = Imbalance, TC = Time Constraints, ToU = Time-of-Use Tariffs.
Trade represents the scenarios in which the battery is only used for trading electricity. With value stacking, the battery is also used to serve demand and store solar energy.
Mitigation events, new congestion events, and charging events are counted per 15-minute interval.
Costs are reported in thousands of euros (K €) per year.

Scenario	Mit. Events	New Cong.	Charging During Cong. Events	Costs
2024[1]	–	–	–	–
DA – Trade	**297**	31	43	-95.6K
IMB – Trade	128	**185**	178	**-377.7K**
DA – Trade (TC)	196	18	17	-71.8K
IMB – Trade (TC)	92	108	87	-291.7K
DA – Trade (ToU)	295	31	44	-95.5K
IMB – Trade (ToU)	128	**185**	**179**	-377.5K
DA – Value Stacking	**260**	6	9	2763K
IMB – Value Stacking	161	**125**	150	**2481K**
DA – Value Stacking (TC)	163	3	2	2787K
IMB – Value Stacking (TC)	120	73	65	2567K
DA – Value Stacking (ToU)	**260**	6	9	2767K
IMB – Value Stacking (ToU)	161	**125**	**151**	2485K
2030[2]	–	–	–	–
DA – Value Stacking	1155	652	287	4105K
IMB – Value Stacking	1124	905	1240	**3517K**
DA – Value Stacking (TC)	854	640	236	4157K
IMB – Value Stacking (TC)	1005	815	869	3696K
DA – Value Stacking (ToU)	**1157**	650	286	4112K
IMB – Value Stacking (ToU)	1125	**906**	**1242**	3523K

[1] Baseline already congested periods (2024): Trade = 746, Value Stacking = 575.
[2] Baseline already congested periods (2030): Value Stacking = 5392.

Contents

Nomenclature

List of Abbreviations

ABM	Agent-Based Modelling
ACM	Authority for Consumers and Markets
API	Application Programming Interface
BESS	Battery Energy Storage Systems
CBC	Capacity Limitation Contract
CoSEM	Complex Systems Engineering and Management
CSC	Capacity Steering Contract
DAM	Day-Ahead Market
DR	Demand Response
DSO	Distribution System Operator
ESS	Energy Storage Systems
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
GSA	Global Sensitivity Analysis
HEMS	Home Energy Management Systems
ISP	Imbalance Settlement Period
kW	Kilowatt
kWh	Kilowatt-hour
LIBs	Lithium-ion batteries
LV	Low-Voltage
MILP	Mixed-Integer Linear Programming
MOLP	Multi-Objective Linear Programming
MSR	Medium-Voltage Substation (Middenspanningsruimte)
MV	Medium-Voltage
MVA	Megavolt-Amperes
MW	Megawatt
OaT	One-at-a-Time
PV	Photovoltaic
PyPSA	Python for Power System Analysis
R-BESS	Residential Battery Energy Storage Systems
RES	Renewable Energy Sources
RR	Replacement Reserves
ToU	Time-of-Use
TSO	Transmission System Operator
USC	Unintended Storage Cycling

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Introduction

1.1. Problem Statement

In alignment with the Paris Agreement, the European Union has developed a long-term strategy to achieve climate neutrality by 2050 (European Commission, 2020a). To effectively implement this vision, all EU member states have formulated national strategies with a minimum time span of 30 years (European Commission, 2020b). The Netherlands, in particular, has set their goal of reducing carbon emissions by 95 percent by 2050 compared to 1990 levels (European Commission, 2019). A key driver of this transition is the electrification of the energy system, with a target of producing 100 percent of electricity from renewable sources by 2050. However, this shift presents several challenges that must be addressed.

A significant challenge related to the transition to renewable energy sources (RES) in the Netherlands is the increasing pressure on the national electricity grid. Although the shift to renewables is critical for achieving climate targets, it has also led to a growing problem of grid congestion, particularly in densely populated and industrialized regions. Grid congestion occurs when the electricity infrastructure is unable to accommodate and balance fluctuations in supply and demand, thereby constraining both energy generation and consumption. This imbalance results from the intermittent nature of RES, which contrasts with the steady and predictable supply of fossil fuels (van der Holst et al., 2025). As illustrated in Figure 1.1, almost all regions in the Netherlands are now experiencing some degree of congestion, a concern acknowledged by both the grid operators and the government (Netbeheer Nederland, 2025; Rijksoverheid, 2025a). This figure includes congestion for electricity consumption, however feed-in congestion on the consumer side occurs as well.

A primary factor contributing to grid congestion is the rapid expansion of solar and wind energy, while the development of the grid infrastructure has laggard. As a result, the transmission of renewable electricity has become increasingly challenging. Netherlands Environmental Assessment Agency (2024) has already concluded that if congestion is not prioritized as a critical policy issue, it will hinder the Netherlands from meeting its 2030 climate targets and could also put a risk on the 2050 goals. This mismatch between electricity generation and transmission capacity not only delays the energy transition but also slows economic growth, as businesses and consumers face difficulties connecting new renewable projects to the grid (Rijksoverheid, 2025b).

Furthermore, electricity demand is projected to rise significantly with the increased adoption of electric vehicles, heat pumps, and industrial electrification (Bedi and Toshniwal, 2019). Recognizing the severity of this challenge, the Dutch government has introduced measures to mitigate grid congestion, including increased investments in grid infrastructure and the promotion of flexibility through congestion management strategies (Rijksoverheid, 2025b). Congestion management refers to the set of measures used to prevent bottlenecks in the electricity grid by ensuring that electricity supply and demand can be matched within the physical limits of the infrastructure. It has become increasingly critical as a short-term solution, given that expanding grid capacity will take years.

Energy storage systems (ESS), and particularly battery energy storage systems (BESS), have been identified as key flexibility solutions to alleviate grid congestion (Wanapinit et al., 2024). Studies indicate that to meet the European Union's 2050 climate targets, battery capacity in Europe will need to increase to between 80 and 351 GWh, a significant rise from the 35.8 GWh available in 2024 (Golombek et al., 2022).

This research aims to investigate the current integration of BESS in the Netherlands, with a specific focus on the challenges associated with the deployment of BESS in households. The objective is to generate insights that contribute to a resilient and sustainable energy system, supporting the Netherlands' long-term climate ambitions.

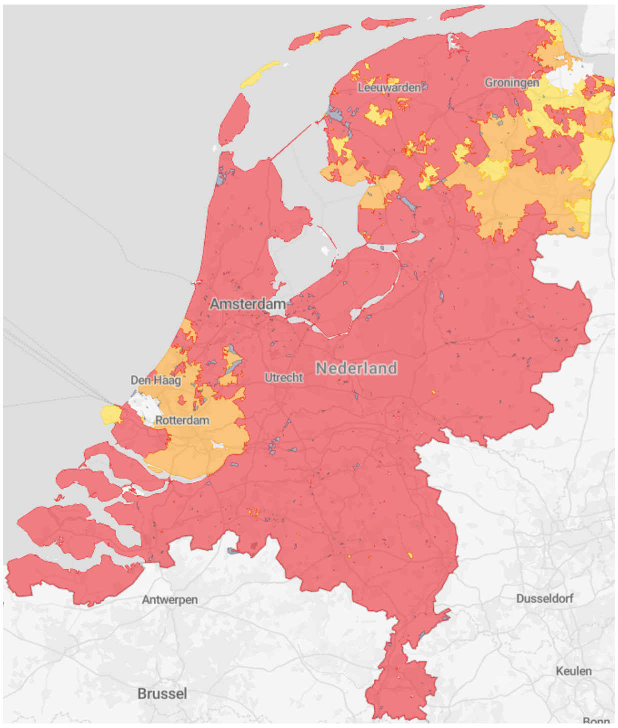

Figure 1.1: Capacity map of the current electricity grid. The yellow color indicates limited transport capacity without a waiting list, orange shows areas under investigation with a waiting list, and red represents a shortage of transport capacity with a waiting list. (Netbeheer Nederland, 2025).

1.2. Research Objective

BESS are widely regarded as a promising technology to mitigate net congestion in electricity grids. By enhancing flexibility, BESS can store surplus renewable energy and discharge it during peak demand, thereby reducing grid strain and improving the overall stability of the electricity network. Their role is particularly relevant in the Dutch energy transition, where increasing shares of renewable energy sources are exacerbating congestion issues.

However, BESS at the household level can also unintentionally increase local net congestion. Research indicates that the most economically beneficial use of battery storage often increases grid congestion rather than alleviating it, due to their capability to trade electricity for profit (CE Delft and Witteveen+Bos, 2023). Moreover, the business case for batteries is largely based on this feature. This challenge occurs particularly in the imbalance market, when R-BESS responds locally to national balancing request. The result is a nationally balanced network, but a high inflow locally resulting in grid congestion (TenneT, 2023; Stedin, 2025). R-BESS can act on the imbalance market if they are operated by aggregators, as a minimum capacity of 1 megawatt (MW) is needed. The ability of R-BESS to participate in energy trading and arbitrage makes their impact on congestion management complex, potentially worsening congestion if not properly coordinated.

To address this challenge, congestion-neutral R-BESS have been proposed as a solution. A congestion-neutral battery is designed to operate in a way that does not contribute to increased peak loads or increase congestion issues. Instead, its charging and discharging patterns are managed to align with grid constraints, ensuring that the battery supports congestion decrease rather than intensifying it. However, as congestion-neutrality is a new design method of battery usage, the impact of this method of usage of R-BESS on techno-economic aspects is unknown. To emphasize, congestion-neutral batteries do not represent a single method, but rather a design approach that guides or constrains battery behavior in ways that help reduce stress on the electricity grid.

To conclude, a research gap remains in understanding how to effectively integrate storage options within the Dutch electrical grid. Further insights into congestion-neutral batteries and how these batteries can effectively be integrated in the grid are needed. Addressing these challenges will be key to realizing the full potential of these integrated technologies, ultimately contributing to more resilient, efficient, and sustainable energy networks. The objective of this research is to analyze the current landscape of R-BESS deployment in the Netherlands and evaluate the impact of congestion-neutral operation. By investigating the trade-offs between grid benefits and economic feasibility, this study aims to provide insights into how congestion-neutral R-BESS can be effectively integrated into the Dutch electricity network. This research will address the following research question:

How can congestion-neutral R-BESS be integrated into Dutch electricity networks to mitigate net congestion while balancing techno-economic trade-offs?

1.3. Subquestions

To address the main research question, the study is divided into three subquestions. These subquestions are designed to build upon each other, transitioning from qualitative exploration to quantitative analysis, and resulting in actionable recommendations. The subquestions arise from the research gaps in section 2.2. The progression ensures that the research captures both theoretical insights and practical applications.

The subquestions are listed as follows:

1: What are the key elements and processes that must be considered for the congestion-neutral integration of R-BESS in the Dutch electricity grid, based on insights from involved actors and literature?

2: What is the impact of different R-BESS applications on grid impact and economic feasibility?

3: What is the impact of integrating congestion-neutral strategies on grid impact and economic feasibility and how robust are the results?

The approach for addressing the subquestions will be elaborated in detail in section 3.1. In addition, the framework of grid impact, economic feasibility, and robustness will be explained in that section.

1.4. Scope

This research is defined by both a technical and geographical scope. It focuses on the integration of R-BESS within the Dutch electricity grid, specifically within medium-voltage (MV) and low-voltage (LV) distribution networks. The study is geographically limited to the Netherlands, taking into account the country's specific grid configuration and energy market conditions. To further scope the research, this research will focus on one medium-voltage substation (MSR) in Monnickendam, where robustness will be tested for three other MSRs.

This thesis specifically focuses on R-BESS due to the limitations inherent in alternative grid flexibility methods such as demand response flexible generation, and network interconnection. The demand response faces significant barriers, including passivity of consumers, limited market awareness, and practical difficulties in real-time behavior adjustment, leading to suboptimal participation and effectiveness. Flexible generation options are similarly constrained by the declining availability of traditional dispatchable sources, such as gas and coal, and the impracticality of hydroelectric solutions in the Netherlands. Lastly, network interconnection and expansion provide significant long-term benefits. However, current grid congestion and the extended timelines required for infrastructure upgrades make them insufficient for tackling short- to mid-term congestion challenges. Consequently, R-BESS presents a scalable, flexible, and technologically mature alternative, capable of effectively responding to both immediate congestion management requirements and longer-term grid integration objectives. An in-depth reasoning, including literature, why the decision was made to focus on R-BESS can be found in Appendix A.

As illustrated in Figure 1.2, the scope is restricted to the distribution network, with a focus on medium-voltage (20-10 kV) and low-voltage (0.230 kV) networks. The transmission network, managed at high voltage levels, is outside the scope of this study. Instead, the research will examine how household batteries, connected at the LV level, interact with the MV grid through distribution substations. The load levels of the MSR will be retrieved by Liander, and therefore the scope is further restricted to the distribution network which is managed by Liander.

The primary subject of analysis is R-BESS, which means energy storage systems installed behind the meter in residential buildings. As the particular MSR of this study is connected to 3276 small-scale consumption connections, the scope is narrowed down to 3276 households. In this research, the R-BESS is modelled as being operated by an aggregator. This implies that individual household batteries are centrally coordinated to optimize collective performance, for example by responding to market signals or grid conditions as a single unit. Although other types of storage solutions, such as large-scale batteries at commercial or industrial sites, may be referenced for context, they are not the focus of this thesis. Furthermore, vehicle-to-grid applications, although relevant to decentralized storage, are not explicitly considered within the scope of this study.

This research aims to analyze the techno-economic feasibility of integrating household batteries into the MV/LV distribution network. It will assess the role of different R-BESS applications within the existing infrastructure, considering the implications for distribution system operators (DSOs). Moreover, the impact of congestion-neutral strategies will be researched. The study does not extend to transmission system-level considerations or broader European networks.

By maintaining this clear focus, the thesis ensures a structured analysis of the Dutch MV/LV grid, the role of congestion-neutral R-BESS, and their interaction within the distribution network.

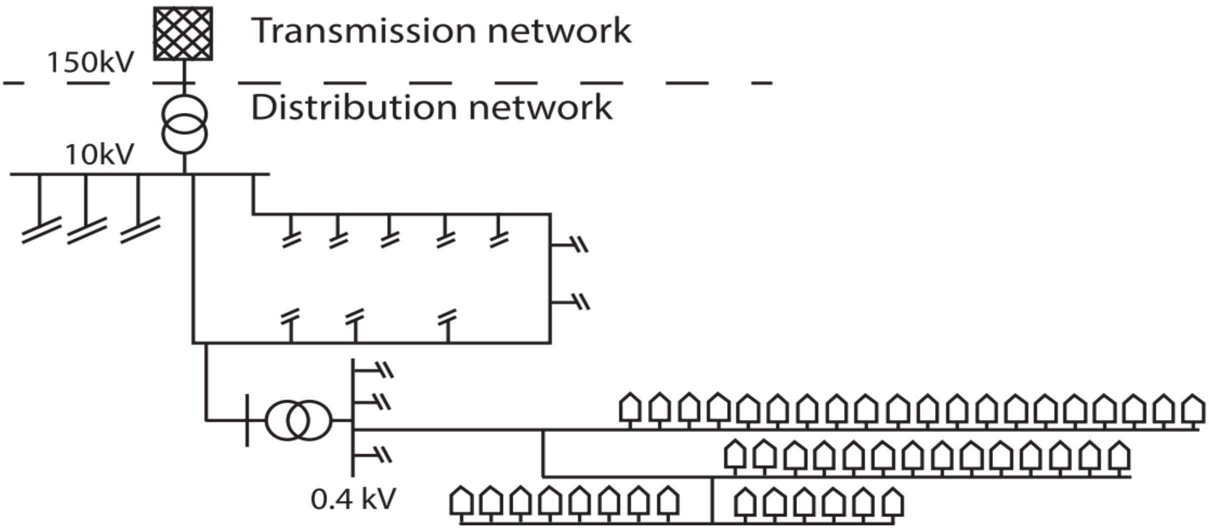

Figure 1.2: Elictricity distribution network within the Netherlands (Nijhuis et al., 2016). The dashed line shows the boundary of this research.

1.5. Research Approach

The approach is designed to explore various R-BESS applications, to incorporate perspectives and points of view from all involved actors, and to ultimately research different scenarios. Given the complexity of the research problem and the exploratory nature of the study, a mixed-method research design is adopted, which is best for combining qualitative and quantitative elements (Lund, 2012).

This study emphasizes the useful application of research to address real-world challenges and is based on a pragmatic point of view. To provide a comprehensive understanding of the problem, pragmatism allows the integration of qualitative and quantitative methodologies. It places a high value on methodological adaptability, allowing the choice of approaches most suited to accomplishing the goals of the study (Creswell and Poth, 2013).

The research design follows an exploratory sequential design, which starts with qualitative research to build foundational insights, and to create input for quantitative modelling (Ivankova et al., 2006). The design is visualized in a research flow diagram and can be found in Section 3.1. This structure ensures that the study captures a quantitative part to model different scenarios based on the qualitative analysis. The key steps include:

1. **Exploratory Qualitative Phase**: Collect and analyze data through literature reviews and interviews to identify the environment of the study and the knowledge gap. Furthermore, data is extracted to prepare for the quantitative phase. The information and perspectives of stakeholders and actors will serve as input for the different scenarios modelled in the quantitative phase. A modelling framework is made to show how the scenario's are layered (Appendix E). The extensive Research Flow Diagram is created to show the interaction between the qualitative and quantitative phase (Appendix D).
2. **Quantitative Simulation Phase**: Use findings from the qualitative phase to inform scenario modelling, allowing for the testing of congestion-neutral strategies. However, the research will not flow in a linear process. Modelling will be integrated within the qualitative phase to understand the input needed from involved actors and literature along the way.
3. **Synthesis and Interpretation**: Combine the insights from both phases to formulate actionable recommendations.

1.6. Relation to CoSEM Master Program

This thesis on congestion-neutral battery storage for managing net congestion in the Dutch electricity grid aligns strongly with TU Delft's Complex Systems Engineering and Management (CoSEM) program, specifically the Energy track. CoSEM addresses complex socio-technical challenges by integrating technical innovation, stakeholder management, and institutional frameworks.

Net congestion exemplifies a complex socio-technical problem involving technological, economic, regulatory, and social dimensions. Following CoSEM principles, this research evaluates battery energy storage systems within the broader stakeholder and institutional context, using systems engineering methodologies to propose structured integration strategies that consider practical constraints such as regulations and economic factors.

By incorporating diverse stakeholder perspectives, this research bridges theoretical optimization with practical application, reflecting CoSEM's focus on real-world feasibility. Ultimately, this thesis embodies CoSEM's objectives by integrating technological solutions and policy insights to address the complex system of electricity grid congestion challenges.

1.7. Research Outline

This thesis is structured into six chapters, systematically addressing the integration and impact of congestion-neutral R-BESS within the Dutch electricity network. The chapters build upon each other, from problem identification through detailed analysis, and result in practical recommendations and conclusions.

Chapter 2 Literature Review: This chapter synthesizes academic and grey literature on congestion management and the specific role of congestion-neutral R-BESS. Stakeholder interviews with DSOs, aggregators, and policymakers are integrated to provide practical insights and identify real-world challenges. Moreover, an interview with actor CE Delft will be conducted, as they have published numerous reports and studies in this field. The outcomes set the foundation for scenario development and subsequent analyses.

Chapter 3 Methodology: This chapter explains the mixed-method research design, detailing the PyPSA modelling framework used for scenario analysis. It outlines data collection, scenario development, and the implementation of congestion-neutral constraints. The methodological choices and assumptions are transparently described.

Chapter 4 Results: The results chapter presents quantitative outcomes from the scenario analyses, focusing on grid impact and economic feasibility for R-BESS under various market and operational strategies. Scenarios for 2024 and 2030 demonstrate the effects of different congestion-neutral strategies and market behaviors.

Chapter 5 Discussion: This chapter contextualizes results by comparing them with existing literature and involved actor perspectives, discussing key trade-offs and their implications for grid management. It evaluates the robustness and sensitivity of findings, providing insights into practical implementation considerations.

Chapter 6 Conclusion: The final chapter summarizes key findings, directly addressing the research question and subquestions. It offers actionable recommendations for stakeholders and actors, emphasizing practical strategies for integrating congestion-neutral R-BESS. Directions for future research are also provided.

2
Literature Review

In this chapter, a literature review on core concepts is conducted to identify the knowledge gap. The section thereafter wraps up with an analysis of the performed interviews. The purpose of this literature review is to provide a comprehensive understanding of R-BESS applications within the Netherlands. The R-BESS will first be compared to other methods to substantiate why batteries are promising and why that is the focus of this research. Secondly, the academic knowledge gap will be addressed based on the state-of-the-art research. The knowledge gap will be followed up by elaborating on the concepts that need to be understood for R-BESS integration. This chapter concludes by analyzing interviews relating R-BESS applications.

2.1. Core Concepts

To address the identified gaps in the literature, it is essential to first establish a comprehensive understanding of the R-BESS landscape. This chapter provides the necessary contextual background by synthesizing insights from both scientific literature and grey literature, including reports from key market actors such as TenneT and Stedin. The chapter systematically identifies and examines the core technical, economic, and institutional dimensions relevant to household battery integration. Developing an understanding of these components forms the foundation for identifying applicable R-BESS applications and the congestion-neutral strategies implemented in the modelling framework.

This qualitative foundation ensures that the their is a solid foundation for the conceptualization, formalization and implementation of this research. It captures in total four core concepts. These core concepts include the characteristics of R-BESS, the operation of R-BESS, related revenue streams, and to conclude the concept of congestion-neutrality.

2.1.1. R-BESS

The European R-BESS market has experienced rapid growth due to increased electricity prices, concerns about energy security, and the expansion of residential solar photovoltaic systems (Wanapinit et al., 2024). In 2021, the market doubled to 2.3 GWh and forecasts project a strong continued upward trend, reaching 32.2 GWh by 2026 in a medium growth scenario (Europe, 2022). DNV (2025) defined a residential battery as an energy storage solution designed for use in households. It stores electricity that is typically generated from renewable sources, such as rooftop solar panels, or drawn from the grid during periods of low electricity prices. By allowing households to manage their energy consumption more efficiently, R-BESS can provide backup power during outages, reduce dependence on the grid, and facilitate participation in energy markets. Most residential batteries use lithium-ion technology and are often integrated with smart energy management systems to optimize their performance and interaction with the grid. R-BESS have a power of 2 to 25 kWh and will be installed behind the meter. Thereby these batteries have a life cycle between 10 and 20 years depending on the charging cycle and cost between 2500 and 12000 euros (CE Delft, 2023a).

Home batteries can be used for congestion management in two ways. They can either reduce the peak load of individual households, ensuring that their own energy use does not overload the grid, or they can participate in broader congestion management strategies that stabilize the local electricity network (CE Delft, 2023b). In the first case, batteries store excess solar energy during the day and discharge it during periods of high household demand, reducing strain on the grid and potentially eliminating the need for larger grid connections. In the second case, they can be integrated into congestion management programs, where grid operators provide financial incentives for batteries to charge or discharge at specific times to balance supply and demand across the network. The implementation of household batteries will be explained by 5 scenario's further on in this section.

Despite being one of the leading countries in solar photovoltaic (PV) adoption, the Netherlands has not seen significant growth in residential battery storage. This can primarily be attributed to its net-metering policy which allows households to sell excess solar electricity back to the grid at retail rates. This effectively makes the grid a virtual battery, reducing the financial incentive for homeowners to invest in standalone battery storage. However, the government abolishes the net-metering policy per 2027 for several reasons. First of all, the price of solar panels decreases and the efficiency increases. Secondly, the government wants to stimulate households to integrate demand response to reduce the pressure on the net (Rijksoverheid, 2025c). CE Delft (2022) mentions that this could positively influence the business case of R-BESS, but it will not automatically result in a positive business case.

Integration

To accelerate the integration of RES and to increase grid reliability and flexibility, the demand for R-BESS increases. Moreover, these systems could enhance the operations of DSOs and TSOs and reduce their costs (Eurelectric, 2018). Killer et al. (2020) explain the integration of the BESS as three major parts. A visualization of the BESS within the grid is shown in figure 2.1:

- **The battery system:** The battery system consists of a battery that is connected to a converter, in this case the coupling of the system.
- **The system coupling:** This coupling consists of transferring direct current to alternating current or vice versa. Moreover, the voltage can be regulated depending on high voltage, medium-voltage, or low-voltage applications (Hidalgo-León et al., 2017).
- **Grid integration:** Grid integration covers all possible applications of R-BESS.

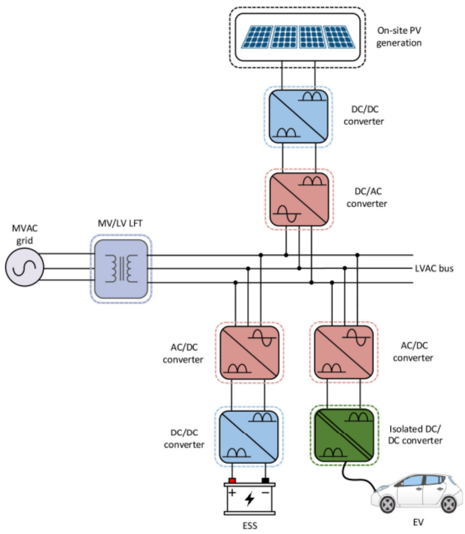

Figure 2.1: Simplistic overview of the integration of a R-BESS within the Dutch electricity grid (Ahmad et al., 2022).

2.1.2. Operation of R-BESS

R-BESS have three main applications, as illustrated in Figure 2.2. The first is arbitrage, where batteries purchase electricity during low-price periods and sell it during peak periods with higher prices, generating revenue from the price difference.

Secondly, with energy balancing, batteries can match supply and demand by trading in balancing markets and the energy markets. With energy balancing, the battery charges or discharges based on the imbalance signal of TenneT. If there is a shortage, the battery discharges, and if there is a surplus, the battery charges. Next to imbalance signals, balancing also occurs by balance service providers who are controlled by the TSO. With Frequency Containment Reservers (FCR), the TSO withholds an amount of reserves determined by the EU to balance the grid when needed (TenneT, 2025a).

The other feature of batteries is congestion management. The battery can reduce congestion by charging during the day to resolve grid congestion caused by electricity feed-in and discharges in the evening to resolve grid congestion caused by electricity consumption (CE Delft, 2023b). Depending on how they are used, R-BESS can help reduce grid congestion, contribute to it, or remain neutral. When properly managed, they can significantly lower peak demand by storing electricity when supply is high and releasing it when demand increases. In some cases, grid operators can directly control battery usage to alleviate stress on the network. However, if batteries charge or discharge during, for example, peak demand hours, they can worsen congestion by increasing pressure on the grid. Ideally, batteries should operate in a congestion-neutral manner, which means they do not increase peak loads or cause additional grid strain (CE Delft, 2023b).

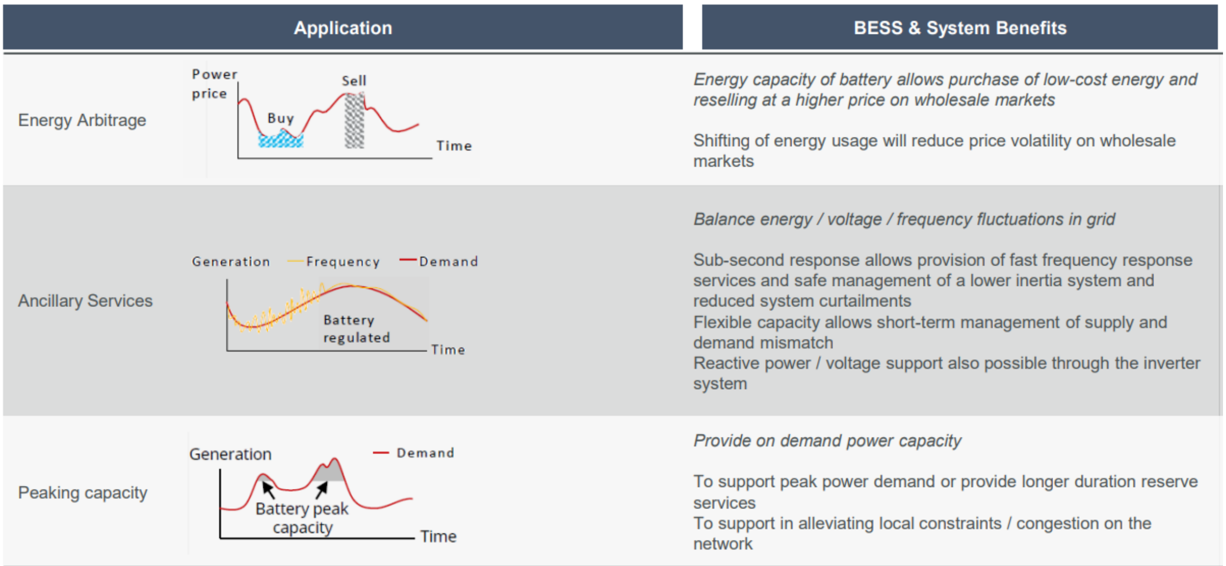

Figure 2.2: Applications of R-BESS (TenneT, 2024b).

The battery operation in practice can be explained by 6 scenarios. These scenario's explain battery integration in relation to the base scenario: a congested grid. The scenarios were performed by CE Delft (2023a). The base scenario represents a situation where congestion occurs without any battery integration. In this case, the electricity grid faces peak demand periods that exceed the available capacity, leading to congestion without any mitigation measures in place.

In the second scenario, a battery system is introduced; however, instead of alleviating congestion, it increases the net load by charging during peak demand periods. This highlights a potential drawback of uncoordinated battery operation, where charging at the wrong time can unintentionally increase the stress on the grid rather than relieve it.

The third scenario, which serves as the core focus of this research, introduces the concept of congestion-neutral battery operation. Here, the battery is strategically controlled to avoid charging or discharging during peak periods, ensuring that it does not contribute to grid congestion. This scenario provides crucial insight into how battery systems can be integrated in a way that does not worsen congestion issues. In later stages of this research, this principle will be further explored and refined. By identifying peak demand periods within the Dutch electricity grid, targeted scenarios can be developed to model the effects of congestion-neutral operation. These models will help assess the feasibility and effectiveness of this approach in real-world applications.

In the fourth scenario, battery discharge is actively utilized to fully resolve congestion. By releasing stored energy precisely during peak periods, the battery reduces the net load on the grid, effectively mitigating congestion. This scenario demonstrates the potential of well-coordinated battery storage in balancing supply and demand.

The fifth and sixth scenarios illustrate ways in which battery storage can help alleviate congestion; however, neither provides a complete solution. While congestion is mitigated to some extent, other grid limitations still persist. The figure on the left represents a scenario in which the primary issue is the result of an overall shortage of available power or insufficient generation capacity to meet demand. In contrast, the right figure highlights a case where the limitation is purely due to capacity constraints within the grid infrastructure, preventing additional power from being transmitted effectively.

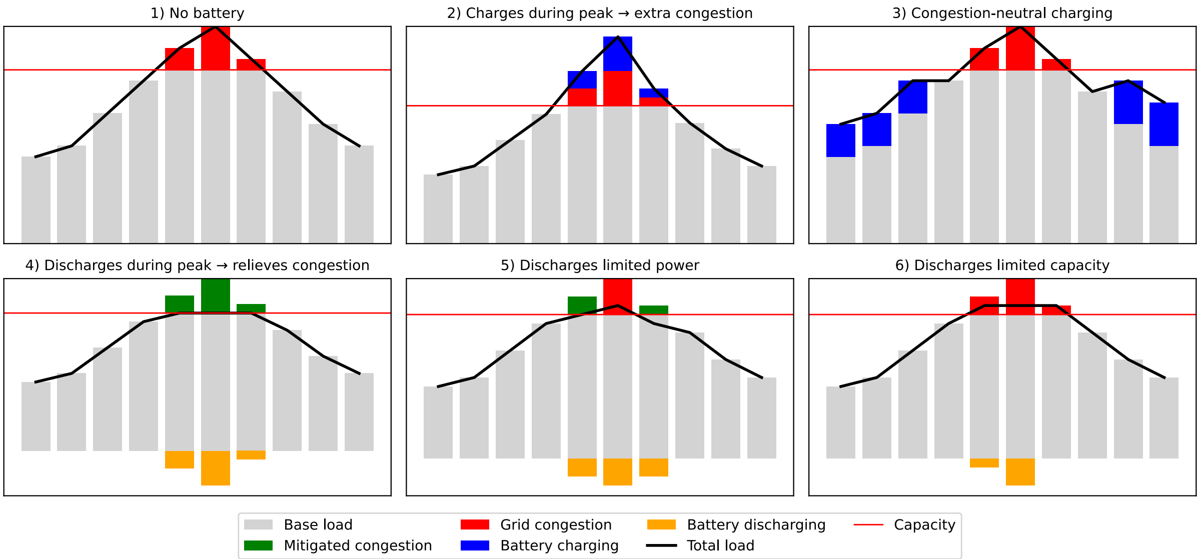

Figure 2.3: Visualization of all six R-BESS different operational scenarios. The figure is an improved version of the visualization used in a research from CE Delft (2023a).

2.1.3. Revenue Streams

To make the investment in R-BESS attractive, a business model is needed to make profit and return the investment. Therefore, this section will elaborate on the organization of the Dutch electricity market, how R-BESS can use this form to gain profit, and how the business model should adapt when R-BESS are implemented congestion-neutral.

Primarily, R-BESS can participate in electricity trading in both the wholesale and balancing markets. Electricity can be traded on the wholesale market through bilateral contracts or through the spot market. The framework of the Dutch electricity market is illustrated in Figure 2.4. The spot market includes the day-ahead market and the intraday market. The day-ahead market closes at noon 24 hours in advance, and the intraday market closes five minutes before the actual electricity supply. After its closure, the Transmission System Operator (TSO) balances supply and demand to ensure security of supply (Tanrisever et al., 2015).

Moreover, R-BESS can generate revenue by acting on the imbalance market. This can be achieved by providing FCR, as discussed in Section 2.1.2. Next to FCR, R-BESS can react on national imbalance signal from TenneT. This applications could potentially increase grid congestion. Additionally, R-BESS can participate in secondary and tertiary control reserves, known as Frequency Restoration Reserves (FRR) and Replacement Reserves (RR) (Fleer and Stenzel, 2016). However, to engage in contractual agreements with the TSO, a minimum capacity of 1 MW, 4 MW, and 20 MW is required for FCR, FRR, and RR, respectively (Kakorin et al., 2014). Because R-BESS have a capacity of less than 1 MW, aggregators can help to combine multiple R-BESS resulting in a capacity larger than 1 MW. Aggregators are explained in detail in Section 2.1.3.

The other revenue stream is based on arbitrage. Where the R-BESS charges at low price and discharges at high prices in the wholesale market. However, as previously mentioned, this behavior can worsen grid congestion. Therefore, R-BESS could also create revenue in congestion markets. This can be done both through congestion management contracts and GOPACS (TenneT, 2024b).

Under congestion management contracts, consumers and producers are required to provide flexibility by adjusting their energy feed-in and demand, either by increasing or decreasing power flows. Providing flexibility, organized by GOPACS, generates financial compensation (TenneT, 2025b). The Electricity Grid Code stipulates that consumers or producers with a contracted capacity exceeding 60 MW must participate in congestion management (Ministry of Justice and Security, 2024).

GOPACS also facilitates direct agreements with grid operators to manage congestion through capacity reduction. These contracts allow parties to reduce their energy capacity either on demand or within a predefined time block. In the Capacity Restriction Contract on demand, parties agree to transport less energy at specific, variable times when requested, in exchange for financial compensation. Alternatively, the Capacity Restriction Contract with a time block involves a fixed reduction in energy consumption or injection at predetermined times, also in return for compensation (GOPACS, 2025).

In addition to these relatively new revenue streams, CE Delft (2023a) underscores that other incentives are needed to scale the BESS investments. One way is a subsidy to incentivize a large battery capacity. Moreover, agreements made to ensure that batteries charge and discharge optimally at the right moments require a high number of full-load hours dedicated to congestion management. A subsidy should incentivize the deployment of such batteries, ensuring their effective contribution to grid stability. Alternatively, a subsidy can support congestion-neutral operation in combination with policies enforcing such behavior. In this case, the subsidy aims to compensate for the financial gap between a business model with a firm grid connection and one without congestion impact.

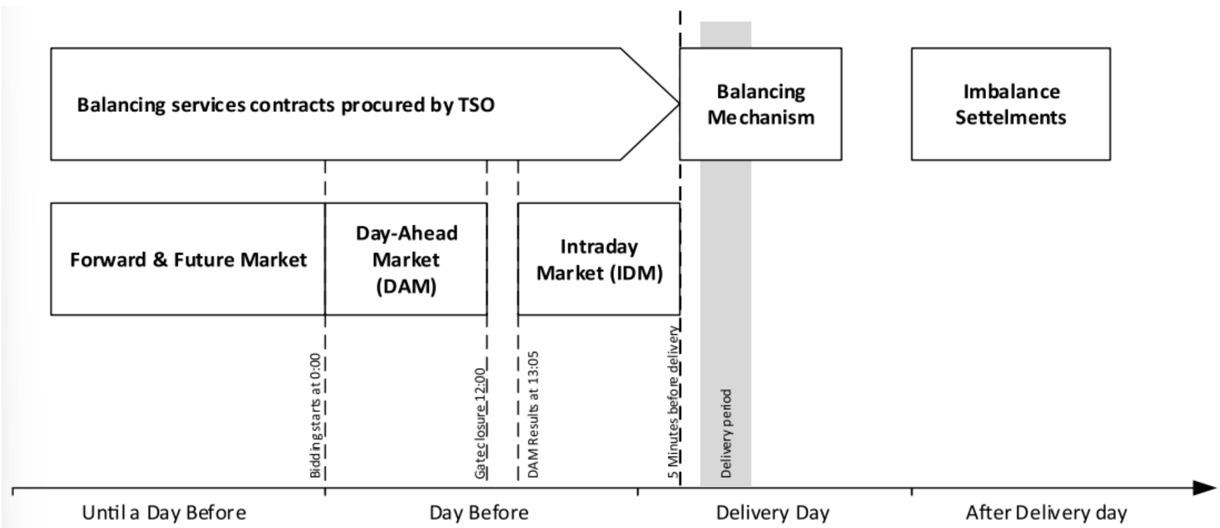

Figure 2.4: The framework of the Dutch electricity market (Kooshknow and Davis, 2018).

Aggregators and the imbalance market

Since the capacity of individual home batteries is too low for direct participation in the balancing market and FCR, households rely on aggregators. Aggregators are companies that pool multiple home batteries to meet the minimum capacity requirements for accessing these markets (CE Delft, 2023b). Their primary objective is to participate in the balancing market to maximize revenue for both prosumers and the company itself. By offering flexibility services, aggregators not only increase their own revenue but also enable distribution system operators DSOs to mitigate network congestion (J. Hu et al., 2018). Although both revenue streams are elaborated on in Section 2.1.3, participation in the balancing market requires additional explanation, as it is closely related to the increase in congestion.

In the Dutch electricity market, the TSO, TenneT, is responsible for maintaining the balance between electricity supply and demand in real time. This is achieved through a market-based balancing mechanism, where market participants submit bids for upward and downward regulation, which are activated when needed. To structure the activation and settlement of balancing power, TenneT categorizes each Imbalance

Settlement Period (ISP), a 15-minute interval, into a regulation state. These states determine the pricing structure for imbalance settlement and influence market participants' trading strategies.

TenneT distinguishes four regulation states based on the real-time balance of the system (TenneT, 2016). Regulation State 0 indicates that no balancing power was required, and the imbalance price is set at the mid-price, the average of the lowest bid for upward regulation and the highest bid for downward regulation. Regulation State +1 occurs when there is a power shortage, requiring upward regulation, and the imbalance price is set by the highest activated bid. Conversely, Regulation State -1 applies when there is an electricity surplus, necessitating downward regulation, with the imbalance price determined by the lowest activated bid. The most complex situation arises in Regulation State 2, where both upward and downward regulation are activated within the same ISP, leading to an adjusted pricing mechanism designed to prevent market distortions.

Regulation State 2 presents significant challenges for battery aggregators. One of the primary challenges is the uncertainty surrounding imbalance prices. In standard regulation states, imbalance prices directly reflect the cost of activated balancing power, allowing aggregators to optimize battery dispatch based on expected price movements. In Regulation State 2, however, the pricing structure is adjusted to prevent reverse pricing, where a power shortage could result in a lower imbalance price than a surplus. Specifically, the price for upward regulation is set at the maximum of the mid-price and the highest activated bid, while the price for downward regulation is set at the minimum of the mid-price and the lowest activated bid. This adjustment reduces price volatility, limiting opportunities for arbitrage and making it more difficult for aggregators to predict profitable charging and discharging moments.

Additionally, the delayed settlement of imbalance prices increases financial risk. Unlike wholesale electricity markets where prices are determined in advance, imbalance prices are only confirmed after the ISP has concluded. This means that aggregators must make real-time trading decisions without certainty about the final imbalance price. In Regulation State 2, where price adjustments can diverge significantly from initial market expectations, aggregators may face situations where they incur losses instead of revenues due to unfavorable pricing adjustments. Aggregators typically deploy algorithmic trading models that analyze historical price patterns to determine optimal dispatch schedules. Moreover, they could predict imbalance signals based on phenomena such as cloud formation and large swarms of birds passing by a wind farm. These models can respond so quickly that they disrupt Regulation State 2. As a result, where TenneT asked R-BESS to balance the market because of a deficit, a surplus is reached within the same ISP. Where aggregators were expecting to earn money, they had to pay the TSO to discharge the R-BESS.

The combination of these factors makes Regulation State 2 a critical consideration for aggregators managing home battery batches. Although imbalance market participation remains a viable business model under normal conditions, the unpredictability and altered price dynamics of Regulation State 2 financial risks. Moreover, as Regulation State 2 occurs more often due to aggregators, these extreme fluctuations increase price volatility and could increase local grid congestion when trying to balance the national network. Therefore, TenneT announced that per 3 December 2024, balance data will be published with a delay of 5 minutes instead of 2 minutes (TenneT, 2024c).

2.1.4. Congestion-Neutral Strategies

In the context of congestion-neutral management, a battery can be connected to the electricity grid using a Capacity Limitation Contract (CBC). This approach is specifically designed for aggregators and not individual household batteries. Under such a contract, the connected entity is subject to restrictions during periods of grid congestion. This ensures that the battery operates in a congestion-neutral manner, as it is only curtailed when the grid experiences capacity constraints. By implementing this approach, batteries can be integrated into the system without increasing existing congestion issues. (Liander, 2025).

A different approach, known as a Capacity Steering Contract (CSC), enables proactive congestion management by dynamically controlling electricity consumption and feed-in (Stedin, 2025). In specific areas, congestion patterns can be forecasted with sufficient accuracy to allow grid operators to notify consumers or prosumers of their maximum permissible energy use within a given time window. This dynamic allocation, typically one day in advance, ensures that the electricity grid remains within operational limits while creating flexibility to connect additional users who would otherwise be restricted by congestion.

In addition to day-ahead flexibility, CSCs can include long-term agreements that set annual limits on electricity consumption or feed-in based on projected local grid constraints. When grid operators foresee an overload, participants are contractually obligated to reduce their demand or supply accordingly. By formalizing such arrangements, CSCs enable grid operators to manage capacity over both short and long time horizons, improving reliability and facilitating the integration of new users without overloading the network.

The feasibility of steering residential batteries as a congestion management tool has been successfully demonstrated in a pilot study conducted by Zonneplan and DSO Liander (Zonneplan, 2024). This pilot, carried out in Arnhem, aimed to explore how households equipped with flexible home batteries and solar panels could contribute to alleviating grid congestion and how to act congestion-neutral. Zonneplan coordinated the charging and discharging by constraining them between 12:00-14:00 and 17:00-19:00. One key finding was that the batteries decreased the number of charging periods during the peak hours of the evening (Zonneplan, 2025). In addition, battery discharging was prevented during sunny afternoons, a period characterized by excessive solar energy generation that could otherwise lead to grid congestion.

Moreover, Dutch grid operators started exploring an indirect approach to enhance the business case for R-BESS. This approach, known as Time-of-Use (ToU) tariffs, replaces fixed grid rates with a variable tariff structure based on electricity consumption per kilowatt-hour (kWh). In this system, electricity prices are lower during periods of low grid load and increase during peak demand, which usually occurs in the morning and evening (Berenschot, 2024b).

The primary objective of ToU tariffs is to incentivize more efficient utilization of intermittent renewable energy generation, particularly PV systems and wind power. By aligning electricity costs with grid demand, consumers are encouraged to shift their consumption patterns, potentially improving grid stability and reducing peak congestion.

CE Delft (2024) conducted an in-depth analysis of the impact of ToU tariffs on the economic viability of R-BESS. Although these tariffs do not generate a direct revenue stream, they contribute to increased cost savings by allowing users to avoid higher grid tariffs during peak periods. This cost-avoidance mechanism effectively enhances the financial feasibility of battery storage investments. Their findings indicate that the implementation of ToU tariffs could shorten the return-on-investment period for R-BESS, reducing it from an estimated 12–18 years to approximately 10–15 years. This indicates that ToU pricing could serve as a crucial policy tool to promote decentralized energy storage and alleviate grid congestion challenges.

2.2. State-of-the-art

As shown in the previous sections, a variety of congestion management strategies are currently available, both for the short and long term. Among these, R-BESS result as a promising solution to mitigate net congestion in the Netherlands. This section aims to identify current research gaps in the integration of R-BESS into the electricity system. Each identified gap will lead to a subquestion, ultimately contributing to the main research question of this thesis.

As a result of the recent development of congestion-neutral R-BESS and their potential to increase local congestion under certain conditions, this state-of-the-art section will mostly rely on grey literature. In this context, grey literature refers primarily to reports, policy documents, and other non-peer-reviewed sources such as those from governmental bodies and energy system actors. At present, there is no scientific literature on this specific topic, which underscores its novelty. This is reflected in its recent appearance on political and strategic agendas, as shown by the ”Regional Energy Strategies” recent publication (National Program RES, 2025) and a parliamentary letter from the Ministry of Economic Affairs and Climate Policy (Rijksoverheid, 2025b). Both sources demonstrate that congestion-neutral R-BESS have entered the public and political agenda only in early 2025. Additionally, another parliamentary letter highlighted the need for congestion-neutral R-BESS, although it did not explain how this should be achieved (Ministry of Economic Affairs and Climate, 2025a. This section will focus on three literature gaps. These gaps are related to congestion-neutral in general, grid impact and economic feasibility of R-BESS and the congestion-neutral impact of R-BESS applications.

2.2.1. Congestion-Neutral Conceptualization

Congestion-neutral refers to charging or discharging behavior of a battery that does not contribute to grid congestion. More specifically, it ensures that battery operations do not increase peak loads on the grid, whether during charging or discharging. For example, a battery may be temporarily turned off during a sunny afternoon when large amounts of solar energy are being fed back into the grid, to avoid adding further strain to the system.

Current research on congestion-neutrality

If R-BESS is used in the electricity market, it has a positive impact on matching supply and demand. However, balancing supply and demand can increase congestion. When the national market is imbalanced, TenneT calls for additional supply or demand, without specifying where this surplus generation or increased consumption should come from (TenneT, 2025a). Therefore, balancing markets can result in higher peak loads in the local network. The periods when the battery charges or discharges extra may overlap with times of already high local grid load, causing BESS increase grid congestion (CE Delft and Witteveen+Bos, 2023). Moreover, trading in the day-ahead market could increase congestion by charging or discharging during peak times. Congestion-neutral R-BESS could tackle the issue with different methods, identified by the DSOs. These methods include both market-based approaches and regulatory mechanisms designed to constrain and guide battery behavior (Netbeheer Nederland, 2024a). One example is ToU tariffs, which incentivize households to shift their energy consumption by varying electricity prices throughout the day. By offering higher grid tariffs during peak demand periods, these tariffs encourage users to discharge stored energy or reduce consumption when the grid is under pressure. The other method is a direct signal from the DSO to turn off the battery in times of high grid load (CE Delft, 2024). This could both be location or time specific, or the constraints could be implemented in a more generic way. TenneT (2024b) also highlights that BESS should be integrated grid neutral. Nevertheless, little is known about the impact of congestion-neutral R-BESS constraints on techno-economic aspects (CE Delft, 2022).

Gap in literature

As the concept of congestion-neutrality is relatively new and no peer-reviewed scientific literature has yet been published on this topic, further insights are required to better understand how congestion-neutral strategies can be effectively implemented. CE Delft (2025a) highlights that local peak loads are difficult to forecast, since market signals related to the imbalance market become available only shortly before the imbalance occurs. In addition, these signals are defined at the national level, which introduces a spatial mismatch. This combination of timing and geographic scale presents a significant challenge for designing effective operational constraints for congestion-neutral battery behavior. A letter from the House of Representatives underscores the need for congestion-neutral constraints and asks Tennet, the DSOs, market parties, and the Ministry of Climate Policy and Green Growth to collaborate on making agreements on how to implement congestion-neutrality, as the increasing amount of R-BESS is increasing the net load (Rijksoverheid, 2025b). A gap results in identifying key elements and processes that must be considered for introducing congestion-neutral constraints. Background information is needed to understand current R-BESS applications and revenue streams. Moreover, to fully understand the challenges surrounding R-BESS integration and their potential contribution to congestion, involved actor insights are essential. In this context, the actors include market parties operating R-BESS for trading purposes, parties introducing constraints on such trading, and advisory entities that provide guidance on how to ensure R-BESS operate in a congestion-neutral way.

2.2.2. Grid impact and Economic Feasibility of R-BESS Application

Grid impact refers to the mitigating or increasing congestion effect of the Dutch medium-voltage grid resulting from R-BESS applications. Economic feasibility refers to the total system costs including the R-BESS application.

Current research on R-BESS applications

Recent studies provide detailed modelling of the business case for R-BESS across various electricity markets. CE Delft (2021) conduct a techno-economic assessment of battery applications in the Dutch market and identify future revenue streams such as FCR and the imbalance market. Similarly, Veenstra and Mulder (2024) use electricity price modelling to assess arbitrage profitability in the day-ahead and intraday markets, demonstrating that even under limited capacity, R-BESS can yield considerable profits when advanced trading strategies are employed. Koolen et al. (2023) complement these findings by modelling spot market flexibility contributions of storage technologies, positioning R-BESS as attractive methods for arbitrage and system balancing in high RES scenarios. Together, these studies highlight the financial case for R-BESS in various revenue streams. In terms of grid impact, several studies investigate the system flexibility the R-BESS can offer (Nitsch et al., 2021; Plaum et al., 2022; Weckesser et al., 2021).

These studies highlight that R-BESS can offer flexibility and reduce congestion by load shaving.

Gap in literature

Despite growing insight into R-BESS profitability, a critical gap remains in understanding how these revenue streams impact grid load profiles. While CE Delft (2021) quantify returns from congestion services and market participation, they do not explicitly analyze whether such participation intensifies or alleviates net load, especially during peak periods. Similarly, Veenstra and Mulder (2024) assess arbitrage performance under multiple market strategies but do not investigate the effects of battery dispatch on residual load or congestion patterns. A recent study by Berenschot (2025) modelled the business case for R-BESS, but referred only briefly to the potential for increased grid congestion. It does not specify how or when this congestion might occur, even though such insights are crucial for effective R-BESS implementation. Several other studies also research the techno-economic aspects of R-BESS, with a focus on maximizing profit or minimizing costs. However, these studies do not address grid impact of these applications (Dam and van der Laan, 2024; Yang and Wang, 2024; Hugenholtz, 2020). As the scale of R-BESS deployment increases, modelling their effect on system load becomes essential to ensure they not only remain profitable, but also contribute to a stable and congestion-resilient grid. Addressing this interaction between profitability and system impact is key for integrated policy and planning.

2.2.3. Congestion-Neutral Impact

Congestion-neutral impact is identified as the impact on load and economic feasibility in comparison with the R-BESS scenarios without congestion-neutral strategies.

Current state of congestion-neutral strategies

The implementation of congestion-neutral strategies for R-BESS is currently in its early stages at the policy level. Recent position papers and reports from Netbeheer Nederland (2024c), Stedin (2023), DNV (2025), and Berenschot (2024a) underscore the need to create clear institutional guidelines and incentives to ensure that batteries contribute positively to grid stability rather than increasing local congestion. They highlight the importance of setting clear regulations to prevent unrestricted battery operations from increasing grid stress. This is particularly relevant given the rapid growth of residential battery installations driven by changes such as the phasing out of net metering and the increased popularity of dynamic electricity contracts. Nevertheless, these parties also recognize the uncertainty about the actual impacts these strategies might have, given their recent introduction and the complexity related to their operational implementation.

A recent study focusing on ToU tariffs indicates promising outcomes, demonstrating their effectiveness in reducing grid load while simultaneously offering economic benefits to consumers and DSOs (CE Delft, 2025b). Research conducted highlights that ToU tariffs can significantly reduce peak loads, facilitating more efficient use of the existing grid infrastructure. Despite these encouraging results observed primarily at the household level, literature addressing alternative congestion-neutral approaches remains limited. Particularly, strategies operating at an aggregator level have not yet been explored. So, there is a need to investigate the impact on the grid and the economic feasibility of congestion-neutral strategies implemented at the aggregator level. This expands the understanding of R-BESS implementation beyond individual household applications.

Gap in literature

Next to the unknown impact on grid stability and economic feasibility of congestion-neutral strategies, other gaps arise from literature. A concern is the relationship between weather conditions and the integration of R-BESS. Although several studies have explored structural uncertainty, which refers to the inaccuracy and incompleteness of models, research focusing on the influence of varying weather conditions remains limited (Schwaeppe et al., 2024). This gap is particularly relevant given that R-BESS operations are highly dependent on renewable energy generation, which is inherently influenced by fluctuating weather patterns. Factors such as solar irradiation, wind speed, and temperature variations can significantly affect both the efficiency and availability of stored energy.

In addition, parametric uncertainty is frequently overlooked in existing studies (Neumann and Brown, 2021). Even when considered, the main focus tends to be on uncertainties related to technology costs, such as fluctuation in battery prices and PV costs, rather than those associated with weather variability (Neumann and Brown, 2023). The neglect of weather-dependent uncertainties can lead to oversimplified models that fail to capture the full range of operational challenges in R-BESS deployment. This limitation is further emphasized in Lombardi et al. (2020), which reviews six studies that examine structural uncertainty but rely on a single year of weather data. To enhance the robustness of the R-BESS integration models, more research is required to assess the impact of different weather conditions in addition to research the parametric uncertainty.

2.3. Interview Analysis

To gain a better understanding of the R-BESS landscape in the Netherlands, several interviews were conducted with key actors. The primary aim was to identify the key elements of a congestion-neutral implementation of R-BESS from an involved actors perspective. These insights contribute to answering the first subquestion, alongside the literature review. Moreover, the interviews help to shape the scenarios used in the modelling phase, thereby contributing to the second subquestion.

As described in Section 3.2.2, interviews were conducted with actors involved in R-BESS operation, those responsible for setting limitations on their operation, and advisory parties. This led to the following actors:

Actor	Role	Focus
CE Delft	Advisor	Assessing the impact of R-BESS on grid congestion and implementation of congestion-neutral strategies.
Alliander	DSO	Setting operational restrictions on R-BESS.
Liander + Zonneplan	DSO + Aggregator collaboration	Piloting congestion-neutral deployment of R-BESS.
Essent	Aggregator	Operating R-BESS in market conditions.

Table 2.1: Overview of actor roles and corresponding interview focus.

Based on the interviews with CE Delft, Alliander, Essent, and Liander in collaboration with Zonneplan, three central themes emerged regarding R-BESS deployment: the business case, the regulatory environment, and the implementation of congestion-neutral strategies.

2.3.1. Business Case – Only Trading vs. Value Stacking

All actors agree that the current business case for R-BESS is at his end, when based on a single revenue stream. Essent emphasized that trading alone, whether in the day-ahead or imbalance market, could generate sufficient returns to justify battery investments. However, this business case is not sustainable, as the amount of R-BESS and large-scale BESS exploded in recent years. They also highlight the misleading marketing of aggregators, which is based only on imbalance profits. Many customers purchase R-BESS systems to benefit from high revenue margins achievable through participation in the imbalance market. While this strategy has indeed yielded attractive returns in recent years, market dynamics are expected to shift considerably. As more flexible assets enter the market and regulatory interventions increase, the margins on imbalance market participation are projected to decline significantly in the coming years, reducing the long-term profitability of this approach. Therefore, the trend shift towards stacking revenue streams. Lastly, it should be noted that many households use batteries mainly for self-consumption in combination with solar PV and tend to avoid market trading due to discomfort with unpredictable automated control.

CE Delft and Alliander underscored this view. CE Delft highlighted that the imbalance market is particularly vulnerable to saturation by large-scale systems, making it increasingly unprofitable in the upcoming years for residential systems. Although many R-BESS currently participate in the imbalance market, this is expected to become unviable. Alliander also expects that passive participation may remain partly feasible, but active roles in, for example, congestion contracts will be dominated by large systems. Self-consumption is expected to become a more stable revenue stream.

Zonneplan and Liander confirm the high current value of imbalance trading, but already observe its limitations. Zonneplan focuses on managing R-BESS, thereby having a relatively limited capacity, and therefore takes more risk in trading. In contrast, Essent manages both R-BESS and large-scale BESS and prefers strategies with smaller margins and lower risk.

All parties agree that a sustainable business model requires value stacking, which includes combining self-consumption, dynamic pricing, market trading, and congestion management. Zonneplan, which previously did not support self-consumption, now considers it essential for long-term robustness. Essent referred to the Belgian model, where value stacking is already the standard. Aggregators typically divide battery capacity between services, for example, reserving 30% for imbalance trading and 70% for the day-ahead market.

2.3.2. Regulation – Stimulating or Obstructing Revenue Streams

All actors indicated that the current Dutch regulatory framework hinders rather than supports R-BESS development. Essent particularly criticizes the double taxation on electricity that is stored and later fed back to the grid. Additionally, net metering creates incentives to trading that run counter to congestion mitigation, as they discourage self-consumption.

CE Delft observed that phasing out net metering may eventually promote battery adoption. However, without a regulatory framework to guide battery operation, this could lead to market-driven behavior that worsens grid congestion. They emphasized the need to include congestion-neutral incentives into market design or contractual frameworks.

Liander and Zonneplan proposed a certification or label for batteries that comply with congestion-neutral principles. Zonneplan recognizes the marketing value of this approach, particularly in response to recent criticism from regulators regarding misleading advertisements (ACM, 2024a). CE Delft agreed that such a label could improve aggregator reputation and help secure future subsidies.

All parties stressed that without government support, subsidies, or tax incentives, there is no viable long-term business case. According to Liander and Zonneplan, integration of R-BESS into energy labels could improve their attractiveness and profitability.

2.3.3. Implementation of Congestion-Neutral Strategies

Although all actors support congestion-neutral R-BESS in principle, their views on implementation differ. The actors mention two potential ways to incorporate congestion-neutral strategies. The first one is applying constraints based on time and location, and the second one is based on ToU tariffs.

Time and Location-Specific Strategies

Alliander emphasized the importance of time- and location-specific contracts, particularly for large systems. For residential systems, generalized restrictions are preferred due to the complexity of managing individual agreements.

CE Delft disagrees with this point of view, as they underline that generic constraints could unnecessary decrease the profitability of the R-BESS and the amount of mitigation effects. They acknowledged that congestion-neutral behavior can be technically modelled, but noted the challenges of practical enforcement. Monitoring battery impacts across many MSRs would require real-time data and advanced control infrastructure, which is not yet available. While they prefer MSR-specific strategies, they recognize that these are not currently feasible.

Zonneplan, in a pilot with Alliander, tested fixed time-block restrictions, constricting between 12:00-14:00 and 17:00-19:00, and found that congestion was rarely worsened. However, their portfolio is too distributed across different MSRs to draw general conclusions. They argue that dynamic signals, such as day-ahead congestion alerts, could balance control and economic value, though this is not feasible for the imbalance market. CE Delft also warned that strict time-based restrictions may reduce the beneficial day-ahead behavior of batteries.

Essent proposed mandatory congestion-support contracts with fair compensation, involving a limited number of intervention hours per year. Like CE Delft and Zonneplan, they opposed broad time-block restrictions and instead emphasized incentive-based collaboration with DSOs. However, since Alliander currently does not support this approach, time-block constraints are considered in this research.

Market-Based Strategies

In addition to implementing operational constraints, a market-based approach is also proposed to influence the behavior of R-BESS. One such approach involves the introduction of ToU tariffs, where the TSO and DSOs aim to increase network tariffs during peak hours. The rationale behind this strategy is to incentivize households to consume more of their self-generated solar energy and to reduce the financial appeal of trading during peak congestion periods. Alliander supports this approach and believes that higher network tariffs during peak times can indeed influence household behavior. However, they also expect that many households will respond not by investing in or relying on batteries, but rather by shifting their consumption patterns through demand-side management, such as adjusting appliance usage or scheduling energy-intensive activities outside of peak periods.

2.3.4. Actor Summary Table

To summarize key insights from the interviews, Table 2.2 provides an overview of the main challenges, current operational practices, future expectations, and preferred congestion strategies of each involved actor. The table highlights the different roles and perspectives of advisors, DSOs, and aggregators regarding the implementation of R-BESS in a congestion-neutral way. It also illustrates the variety of approaches currently taken in the market and the shared recognition that regulatory support and value-stacking are essential for a viable business case. Although each actor faces unique concerns, common themes, such as the need for time- and location-sensitive control and improved market alignment, are widely recognized across actors. In contrast, DSO Alliander underscores the importance of operational practicality.

Actor	Problem	Current R-BESS Operation	Future R-BESS Operation	Congestion Strategies
CE Delft	Grid congestion due to imbalance market trading	Mainly imbalance trading, but market will saturate	Value stacking	Time/location-specific restrictions; ToU tariffs
Alliander	Hard to coordinate individual households	Mainly imbalance trading, but market will saturate	Value stacking	General time restrictions; ToU tariffs
Liander + Zonneplan	Negative publicity due to grid impact and misleading marketing	Imbalance + day-ahead + intraday trading	Value stacking	Certification-based constraints; currently follow time blocks
Essent	Unsustainable business case without subsidies	Day-ahead market trading; avoids imbalance market	Value stacking	Incentive-based location/time contracts with compensation

Table 2.2: Summary of actor perspectives on R-BESS operation and congestion strategies.

3 Methodology

This chapter outlines the methodological framework used to investigate the grid impact and economic feasibility of congestion-neutral R-BESS. Given the complex interplay between battery operations, market structures, and network constraints, this study adopts a mixed-method approach. Qualitative insights from key actors, including grid operators, aggregators, and policy experts, were gathered to understand current practices, institutional barriers, and practical considerations related to congestion-neutral battery operation. These insights inform the development of the quantitative modelling approach, ensuring that it captures relevant real-world dynamics and reflects the needs and constraints of actors within the Dutch electricity system. The quantitative analysis is implemented using Python for Power System Analysis (PyPSA) and formulated as a Mixed-Integer Linear Programming (MILP) problem to simulate R-BESS behavior at the aggregator level across various market and regulatory scenarios.

This chapter is structured as follows. Section 3.1 details the general research method. Section 3.2 elaborates on the qualitative approach and Section 3.3 elaborates on the quantitative modelling process.

3.1. Research Method

To create a comprehensive and effective flow of the exploratory sequential design, and to enhance the link between the qualitative and the quantitative modelling part a more effective methodology is needed. Therefore, a framework from van Dam et al. (2012) is adapted. The framework has been studied in detail, and modifications were made to align it with the research. The final framework consists of the following steps:

1. **System Identification**
2. **Conceptualization**
3. **Formalization**
4. **Implementation**
5. **Model Usage**

The first two steps include the exploratory qualitative phase, the third and fourth steps illustrate the quantitative simulation phase, and the model usage step includes the synthesis step.

The first step is essential for understanding the system organization of R-BESS, including its constraints and boundaries. This step is also elaborated within the literature review. Moreover, the congestion-neutral functioning of R-BESS must be well understood. The conceptualization of the model begins with identifying relevant inputs. This information will be collected through the literature review, supplemented by documents from key stakeholders such as TSOs and DSOs. Moreover, documents from consulting parties such as CE Delft and Witteveen+Bos will be used, given their experience and numerous publications in this field. Potential design principles that ensure battery operation does not worsen peak loads will be identified. Additionally, revenue streams and the applications of R-BESS will be researched.

Furthermore, interviews with relevant stakeholders and actors will provide additional insights into the R-BESS architecture and their perspectives on congestion-neutral R-BESS implementation. The complexity of the issue requires an understanding of the techno-economic dynamics among grid operators, renewable energy producers, and consumers. While initiating and developing the modelling process, interviews will be conducted to capture insights from involved actors and explore their roles and interactions within the system. This phase aims to identify barriers to collaboration, competing interests, and areas where stakeholder alignment could enhance the effectiveness of congestion-neutral strategies. The interview analysis can be found in Section 2.3. By incorporating these perspectives, the research ensures that its findings are grounded in real-world challenges rather than purely theoretical considerations. Constraints and requirements will be identified to inform the modelling process. This step addresses the first subquestion:

> **What are the key elements and processes that must be considered for the congestion-neutral integration of R-BESS in the Dutch electricity grid, based on insights from involved actors and literature?**
>
> *where congestion-neutral = the charging or discharging behavior of a battery does not contribute to grid congestion.*

Following the first two steps, formalization is required to systematically structure the concepts. Real-world concepts must be translated into well-defined representations that can be processed by a computer. This involves developing a formal description of the system, where the concepts and initial network are refined to a model suitable for simulation. Specifically, this phase aims to define the modelling environment in which different analyses can be conducted for optimal solution across the scenario space. A precise definition of constraints and the optimization method must be documented. As the formalization phase serves as a preparatory stage for the implementation phase, no subquestion will be directly addressed in this step.

The implementation step involves the adoption of the formalized concepts within the model. The formulated network, along with corresponding constraints and objective functions, must be implemented in a modelling environment. This will be performed using PyPSA. A more detailed explanation of the environment can be found in Section 3.3.2. The first objective of the implementation phase is to understand how different R-BESS applications, identified in the literature review, perform within the Dutch electricity grid. This phase addresses the following subquestion:

> **What is the impact of different R-BESS applications on grid impact and economic feasibility?**
>
> *in which grid impact = the mitigating or increasing congestion effect of the Dutch medium-voltage grid resulting from R-BESS applications. and economic feasibility = the total system costs of the model.*

Once the model is initialized and implemented, the results can be used to address the third knowledge gap. The results of the model will be analyzed to assess the sensitivity and robustness of R-BESS applications under varying weather conditions and load levels and to evaluate the performance of congestion-neutral R-BESS. With the sensitivity and robustness, the system is tested on performance under different parametric conditions. This phase translates the modelling results into insights that can be presented to stakeholders with different backgrounds. Ultimately, the model results aim to reduce the current lack of understanding and provide a basis for stakeholders to derive policy recommendations. This phase addresses the final subquestion:

> **What is the impact of integrating congestion-neutral strategies on grid impact and economic feasibility and how robust are the results?**
>
> *where robustness = the generalizability of the system towards other MSRs.*

To visualize the interconnection between the subquestions and the research question, and to show the interconnection between the quantitative and qualitative phases, a research flow diagram is made.

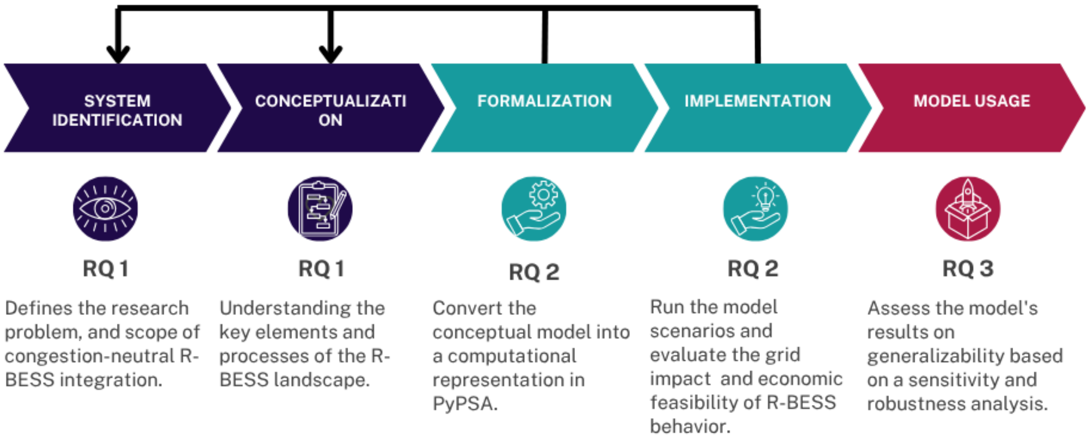

Figure 3.1: A simplified visualization of the research process. The detailed research flow diagram can be found in Appendix D.

3.1.1. Challenges of the Research Method

A mixed-methods approach is well suited for this study due to the multifaceted complexity of the research problem (Timans et al., 2019). Congestion management in electricity networks involves technical and behavioral aspects, which require both qualitative exploration and quantitative validation. These engineering projects involve network operators, consumers, energy suppliers, and municipalities. The interests of all involved parties must be well understood before validation and scenario modelling can start. Their input will play a crucial role in preparing the quantitative phase by defining key requirements, such as congestion-neutral strategies, and the point of view on these implementation from involved actors. This input ensures that the scenarios modelled are realistic and relevant. Without the correct information, there will be no valuable input for quantitative analysis. As mentioned earlier, the modelling process will start early in the process to integrate the stakeholder research more iteratively. The exact scenario modelling application will be elaborated in Subsections 3.3.2 and 3.3.6. By combining these methods, the research captures the complexity of stakeholder perspectives and system interactions while enabling data-driven scenario testing. The exploratory sequential design is therefore particularly suitable for this research.

Using mixed methods in a thesis presents several challenges, particularly when it comes to the integration of qualitative and quantitative data. One of the main difficulties lies in effectively combining these two types of data, as they often require different analysis techniques and interpretations (Almalki, 2016). Ensuring that the insights from qualitative interviews align coherently with the outcomes of quantitative modelling can be complex, and should be done correctly to synthesize the findings. To address this challenge, qualitative data will be interpreted iteratively to shape the quantitative phase. Moreover, the modelling part will start during the qualitative phase to ensure a systematical integration of the stakeholder input. The integration of the qualitative and quantative data is visualized by a more in-depth research flow diagram and can be found in Appendix D.

Additionally, mixed-method research tends to be time-intensive (C.-P. Hu and Chang, 2017). Collecting and analyzing both qualitative and quantitative data involves substantial effort, requiring more time than focusing on a single method. For example, conducting interviews, coding responses, gathering secondary data, and performing scenario modelling all demand careful planning and execution, which can significantly extend the research timeline. To perform the research effectively a time schedule has been developed. The time schedule provides a week-by-week overview of all research activities required for the thesis, ensuring a structured and feasible approach. It is based on the research phases and subquestions, detailing tasks such as literature reviews, stakeholder engagement, modelling, and writing. Key milestones, including the kick-off meeting, midway meeting, greenlight meeting, and defense, are also included with preparation time. Writing and modelling are integrated throughout to maintain steady progress. Visualized as a Gantt chart, the schedule ensures clarity, feasibility, and alignment with the research goals, supporting successful project completion.

3.1.2. Data Security

The research requires qualitative and quantitative data to address the subquestions. For qualitative aspects, internal documents and open source literature will be used for the literature review and in-depth analysis of the R-BESS landscape. In addition, interviews were conducted with experts specializing in R-BESS, as well as stakeholders such as DSOs and aggregators. CE Delft is recognized as an expert organization in the field of R-BESS, while Zonneplan represents one of the active aggregators in the Dutch market. The strong professional network of Witteveen+Bos provided valuable access to these and other knowledgeable interviewees.

For the quantitative input, several data sources are necessary. Load levels will be acquired from secondary data, gathered through internal resources at Witteveen+Bos and their relationships with DSOs. If proprietary data cannot be accessed because of confidentiality issues, publicly available datasets will serve as a substitute.

More information will be sourced from open-access online platforms. For instance, day-ahead and imbalance pricing can be accessed via ENTSO-E, which offers an openly available Application Programming Interface (API). By utilizing the specific Python package for ENTSO-E, users can connect their API key to automatically access pertinent datasets. In the same way, solar irradiation data can be obtained from Copernicus, which provides atmospheric information including solar and wind metrics. Using the Python package atlite, real-time weather and solar data can be obtained and prepared for use directly in the PyPSA modelling framework.

To maintain adherence to ethical standards, the Human Research Ethics Committee has reviewed and authorized a Data Management Plan and Risk Assessment. These measures exist to minimize risks linked to the use of sensitive data and to protect the privacy of individuals interviewed. Moreover, informed consent is secured through a research participation agreement, detailing the interview's objective and the manner in which the gathered data will be utilized and safeguarded. All approved documents are stored at the TU Delft OneDrive and can be shared on request.

3.2. Qualitative Approach

The qualitative stage of this study provided the basis for problem formulation and system identification and serves as foundation for the modelling phase. This stage includes an extensive review of the literature and an analysis of grey literature to understand the benefits and challenges of R-BESS integration. Moreover, interviews were conducted to gain more insights about R-BESS and congestion-neutral impact. Both grey literature and expert insights are needed because of the lack of scientific research on the impact of R-BESS on congestion and how to integrate congestion-neutral constraints. As a result, this study addresses current challenges in the Dutch grid and includes ideas from industry experts, resulting in the model reflecting practical challenges.

3.2.1. Literature

The review began by exploring academic literature on congestion management within electricity networks, with a particular focus on the Dutch context. This phase aimed to define the core concepts to address congestion. Building on this foundation, the focus shifted to literature that addresses why R-BESS should be the focus of this thesis over other congestion management strategies. Both parts can be found in Appendix A. Academic studies were reviewed to evaluate the technical characteristics, economic viability, and operational flexibility of R-BESS.

To complement and contextualize the literature, a follow-up step involved integrating grey literature from key actors in the Dutch energy sector based on the core concepts of this research. These core concepts include the characteristics of R-BESS, the operation of R-BESS, related revenue streams, and the concept of congestion-neutrality. This type of literature is needed to understand what congestion-neutrality is and how the behavior of R-BESS can result in increasing congestion on the grid. Reports and technical documents from TenneT, DSOs and other marktet parties were included to gain insights into practical different applications, multiple revenue streams, and real-world operational constraints. These sources were particularly valuable for identifying different R-BESS implementations, and how these applications could result in both congestion mitigation and congestion increase.

In the final stage, the review turned to identifying gaps in the current state-of-the-art. Particular attention was paid to understanding congestion-neutral R-BESS and how the impact of R-BESS on load levels, with and without congestion-neutral strategies, is modelled. The insights of the literature gaps helped to shape the further literature review, who to interview and how to structure the modelling approach.

By incorporating these applied perspectives, the literature review ensured that the research remained grounded in the current Dutch policy and market environment. Together, these elements formed a coherent and multidimensional foundation for the modelling and scenario analysis that follows, linking scientific literature with practical relevance.

3.2.2. Interviews

Semi-structured interviews were held with different involved parties. Semi-structured interviews are beneficial because there is a specific focus of the interview while also ensuring space for follow-up questions and exploring interesting topics derived from the interview (Adeoye-Olatunde and Olenik, 2021). As noted earlier, the impact of R-BESS on grid congestion is a relatively recent development, and to date, there has been no scientific research specifically addressing this issue. Given the limited scientific literature on this topic, insights from market parties are valuable to gain an understanding of the current challenges. The actors for this research are divided into three groups:

- **Market parties operating R-BESS**: These are companies or aggregators that use R-BESS to trade in energy markets, such as the day-ahead or imbalance markets. Their primary goal is to optimize revenue streams while navigating technical and regulatory constraints.
- **Grid operators restricting R-BESS operations**: Primarily DSOs, these stakeholders impose constraints on when and where R-BESS can charge or discharge. Their main objective is to prevent battery operations from increasing local grid congestion.
- **Advisory parties shaping congestion-neutral frameworks**: These include policy advisors, consultants, and research institutions that provide guidance on how to design and implement rules or mechanisms to ensure R-BESS operate in a congestion-neutral way.

First, all market parties operating R-BESS are stakeholders of this context. Since participation in the imbalance market requires a minimum capacity of 1 MW, individual households do not meet this threshold. As a result, aggregators play a crucial role by bundling smaller battery systems to collectively reach the required capacity. This makes aggregators key stakeholders in the operation and market integration of R-BESS, particularly in enabling access to flexibility markets such as the imbalance market. Moreover, DSOs are particularly valuable to this research as they need to make agreements with aggregators. In addition, the consultancy firms are commissioned by the ”Landelijke Actieprogramma Netcongestie” to provide advice on the role of household batteries in relation to emerging congestion challenges. Their findings offer practical input that can further inform this study.

The purpose of the interviews was to collect information on:

- The present and future role of R-BESS home in the Netherlands energy system.
- Problems and advantages related to the integration of battery storage on a variety of scales.
- Regulations and market mechanisms that affect the economic justification of household batteries.
- Thee stakeholders’ point of view on how to integrate congestion-neutral strategies.

The qualitative data obtained as a result of these interviews provided a understanding of the congestion issues related to R-BESS and how different parties view restricting those batteries. The semi-structured interviews were based on a predefined set of questions, while also allowing room for follow-up questions that emerged naturally during the conversation. The set of standard questions is included in Appendix C. To ensure completeness and accuracy, each interview was recorded and subsequently transcribed. A summary of the transcripts has been prepared and is available upon request.

3.3. Quantitative Approach

The quantitative phase of this research builds on the insights gained from the qualitative analysis. Its objective is to systematically model and evaluate the grid impact and economic feasibility of different R-BESS applications, with and without congestion-neutral strategies. This section first outlines the optimization approach and modelling environment to clarify the context in which the quantitative analysis is conducted. Afterwards, the approach follows a structured process consisting of four key phases. First, in the conceptualization phase, qualitative insights and system understanding are translated into a formal representation of the electricity network and battery behavior. Second, during the formalization phase, this conceptual model is transformed into a mathematical optimization framework suitable for simulation within PyPSA. The implementation phase then focuses on developing and running the model under a set of predefined scenarios that reflect different R-BESS applications. Finally, the model usage phase involves applying sensitivity and robustness analyzes to assess how outcomes vary under different assumptions and uncertainties. Together, these steps provide a comprehensive basis for answering the research questions and subquestions related to the role of congestion-neutral R-BESS in the Dutch electricity system.

3.3.1. Optimization Approach

To model energy systems, various different modelling methods can be used. Methods such as Linear Programming, MILP, Agent-Based Modelling (ABM) and Multi-Objective Linear Programming (MOLP) are often used as programming methods within energy related system studies.

In this research, a MILP approach is applied. Given that the study focuses on a single, well-defined objective and models the R-BESS from the perspective of an aggregator, alternative approaches such as MOLP and ABM are not required. MILP is adopted because both continuous and binary variables are integrated in the model. The exact reasoning behind the binary values is explained in the next section. However, this introduction of battery values comes at the cost of increased computational complexity. Introducing binary variables transforms the linear optimization problem into a MILP, which is significantly more demanding to solve. Despite this trade-off, the binary formulation remains a robust and widely used method for addressing unintended storage cycling in power system models. After testing the computational time of the MILP, the decision was made to include the binary variables.

System artifact

Out of PyPSA's documentation and literature about energy system models, one main modelling artifact was discovered. This artifact is called unintended storage cycling (USC). With USC, the model can store excessive electricity due to simultaneous charge and discharging of the battery. The issue has to be tackled because storage cycling occurs in energy system models, but can not occur in real BESS. In 14 out of 19 researched energy system models, USC has been observed. In the remaining 5 models, it is not known if it is observed or not (Kittel & Schill, 2022).

In the case of the model used for this research, USC occurs when the battery is already fully charged and electricity prices are negative. Because the efficiency of the battery links is 0.91, the model can increase revenue by making energy disappear with USC. According to Parzen et al. (2023), USC can significantly distort system operation by increasing the utilization of storage and renewable generation by up to 23% and 5%, respectively.

An option to tackle USC is to add marginal costs. These marginal costs are not real-world costs, but additional costs. Adding those costs can create a situation where a model with USC is less profitable than a situation without USC. These marginal costs can be added to both the store component and the charge and discharge links. However, adding those costs can significantly change the optimization problem and therefore need to be tested (Parzen et al., 2023). A test was conducted to determine the minimal marginal costs required to completely eliminate UCS. The results showed that marginal costs had an excessively large influence on the optimization outcome. Therefore, another method had to be chosen.

An alternative approach to eliminate unintended storage cycling is the introduction of binary variables into the optimization model. These variables enforce mutually exclusive operational states, charging or discharging, by ensuring that both actions cannot occur simultaneously. This method has been applied in various energy system models, particularly those incorporating unit commitment formulations, where binary decision variables are already used to model generator on/off states (Schill et al., 2017).

By assigning a binary variable to the storage unit's operational mode, the model is explicitly restricted to either charge or discharge at any given time step. This modification prevents energy from being cycled artificially within the same time period, thereby aligning the model's behavior more closely with the physical limitations of real battery systems.

3.3.2. Modelling Environment

PyPSA is an open source modelling framework written in Python, ensuring transparency, adaptability, and reproducibility in energy system studies. Unlike private tools, PyPSA allows full access to model formulations, enabling researchers to refine optimization approaches, integrate novel constraints, and validate results independently. Open source models encourage collaboration, improve accessibility, and thereby increase quality (van Ouwerkerk et al., 2022). The active developer community continuously enhances its functionality, while open-access data sources, such as ENTSO-E network datasets, can be easily incorporated for real-world analysis.

PyPSA is highly adaptable, supporting a wide range of grid configurations but, in particular, is focused on high-voltage networks. Therefore, the model needs to be adjusted properly to represent low- and mid-voltage networks. Its modular structure allows for a detailed representation of distribution energy networks, including transformers, storage options, and generators. The overview of the PyPSA components that will be used during the conceptualization phase is shown in Table 3.1. Custom constraints can be introduced to reflect grid-specific strategies, which is valuable for modelling congestion-neutrality (Brown et al., 2018).

In addition to standard optimization techniques, PyPSA offers built-in support for rolling horizon optimization and can solve MILP. As rolling horizon and MILP will be used to address the second and third subquestion, using PyPSA is advantageous because it integrates the features within its optimization framework, allowing optimization without requiring external modifications or additional solver. Moreover, PyPSA can integrate detailed R-BESS modelling, incorporating energy and power constraints, efficiency factors, and dynamic charging and discharging schedules. Through time series optimization, the framework determines how storage assets interact with market signals, providing information on peak shaving, self-consumption enhancement, and grid support services (Brown et al., 2018). The model also allows R-BESS to participate in congestion management schemes and market mechanisms, optimizing revenue streams while ensuring network stability.

Component	Description
Bus	Fundamental nodes to which all other components attach.
Carrier	Energy carrier (e.g., wind, solar, gas, etc.).
Load	A consumer of energy.
Generator	A generator whose feed-in can be flexible, subject to minimum loading, minimum down/up times, or variable according to a given time series of power availability.
Storage Unit	A device that can shift energy from one time to another, subject to efficiency losses.
Store	A more fundamental storage object with no restrictions on charging or discharging power.
Shunt Impedance	An impedance in shunt to a bus.
Line	A branch that connects two buses of the same voltage.
Transformer	A branch that connects two buses of different voltages.
Link	A branch with a controllable power flow between two buses.

Table 3.1: Network components and their descriptions (Brown et al., 2018)

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3.3.3. Conceptualization

After identifying the system and mapping the landscape of R-BESS, the next phase involves translating this understanding into modelling concepts. While readers of this research may understand how a battery operates or how the energy market functions, a computational model requires these concepts to be expressed in a formalized, machine-readable format. Therefore, the system will be conceptualized based on insights from the literature and expert interviews, while also considering the modelling capabilities and limitations of PyPSA. This conceptualization will define the components, boundaries, and relevant constraints of the system to guide the development of the model.

System Components

For modelling the electricity network, the energy system needs to be conceptualized based on PyPSA's representation. The components are listed in Table 3.1, and most of them are used. This model includes the main components of the electricity system, namely a bus (representing household, MSR and electricity grid), load (demand), generator (PV and energy market generators), store (batteries), and transmission links. The interaction between these elements is modelled over a given period, with a 15-minute time resolution. A 15-minute resolution is chosen for this model to align with the Dutch electricity markets. The imbalance market operates with 15-minute settlement periods and the day-ahead market clears on an hourly basis. This resolution ensures that the model be optimized in a realistic and computationally manageable way.

The visualization of the model is illustrated in Figure 3.2. This network is the outcome of the conceptualization and formalization phases. It is included here at the beginning to provide a clearer understanding of the following sections. The figure illustrates the model components using color-coded elements: data inputs are shown as green boxes, generators as purple ovals, buses as blue circles, and the storage component as a yellow cylinder. The black arrows represent the physical links between the components, while the red arrows indicate the data input. Energy flows originate from the generators and are routed either through the electricity grid and the MSR to the household, or directly to the household in the case of local PV generation. The model aggregates demand and storage at the household level, representing a single household and one R-BESS. As such, it simulates the behavior of an aggregator that coordinates a portfolio of household batteries under unified control.

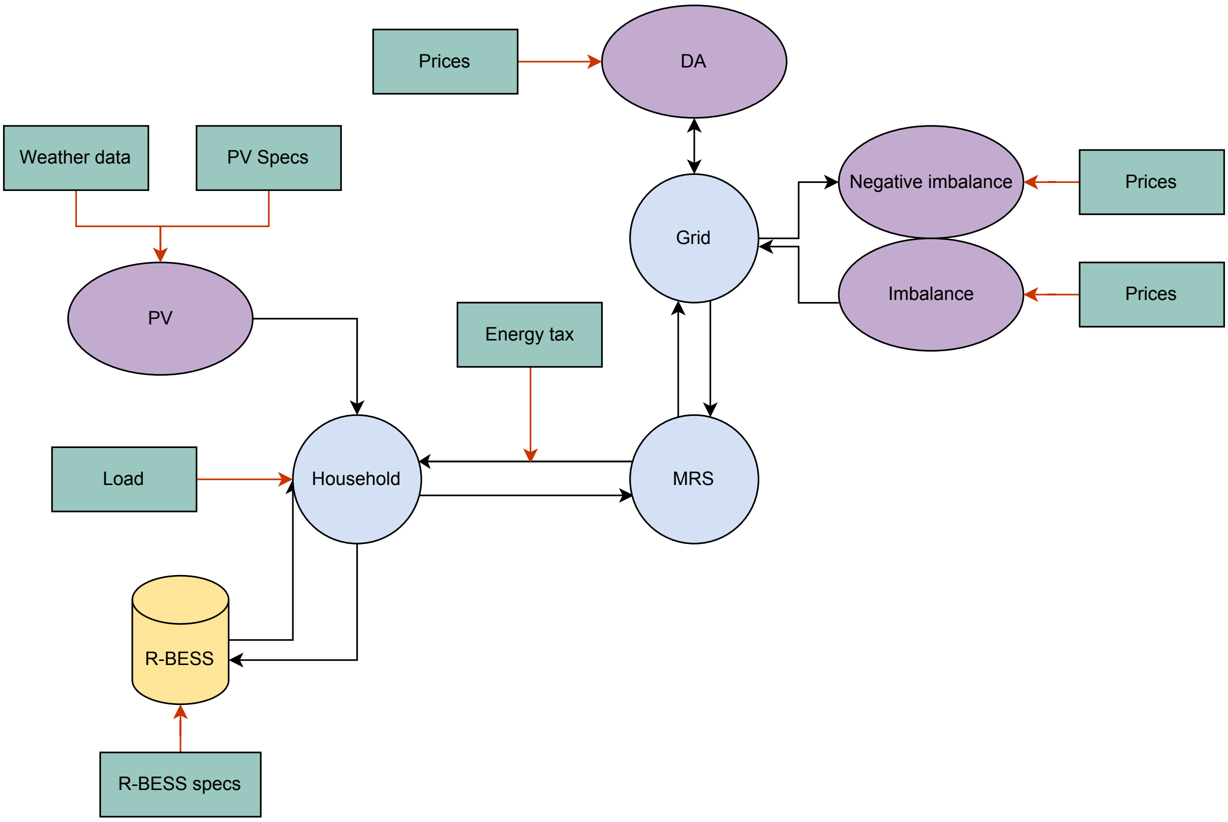


Figure 3.2: A visualization of the network which is used in the PyPSA modelling.

1. Bus

   The bus forms the core of the network, which consists of three distinct buses. The first bus represents the MSR, serving as the central hub where electricity is collected and distributed to medium- and low-voltage (MV/LV) stations. The Monnickendam distribution MSR has a capacity of 11.2 megavolt-amperes (MVA), representing the apparent power of the network, which comprises both active and reactive power. Reactive power is the component of electrical power that cycles between the generator and the grid, rather than being converted into usable energy, as it is 90° out of phase with the voltage. Although it does not contribute to active power, it is essential for maintaining voltage stability in the grid (TenneT, 2019).

Since this research utilizes 15-minute load levels of the MSR in kilowatt-hours, both the load levels and the MSRs capacity must be converted appropriately. Load levels are converted to kilowatts , while the apparent power capacity must be adjusted based on the power factor, which converts the apparent power into active power (MW). For this study, the minimum power factor used by DSOs, namely 0.85, is applied (Stedin, 2008; Enexis, 2008). Consequently, the effective maximum active power capacity of the MSR is 9,520 kilowatt (kW). The MSR facilitates bidirectional electricity flow, allowing electricity to be supplied to households and fed back into the grid.

The household bus represents the electricity demand in the network, with some households incorporating R-BESS. The electricity grid node consists of a day-ahead and imbalance generator that supplies electricity at variable prices.

PyPSA complies with Kirchhoff's Voltage Law, which requires that the sum of all incoming and outgoing power in each bus always equal zero. This ensures that the energy input from the generators and batteries is continuously balanced with the energy demand and the losses of the network, maintaining the stability of the network.

2. Load

The load in the model represents the electricity demand of the household, which varies every 15 minutes. This requires a time-dependent demand function that accounts for daily and seasonal fluctuations. PyPSA optimizes energy flows within the network under the constraint that demand must always be met. If this is not possible, the model generates an error, indicating that demand cannot be satisfied within the given constraints, such as limited generation capacity or grid congestion. For the model, the load levels from 2024 to 2032 are obtained by Liander. These are forecasts based on the load levels of 2023. This data set includes the load levels of the MSR measured every 15 minutes, represented in kW. The fine temporal resolution enables precise modelling of battery charging and discharging activities, particularly when synchronizing battery functions with peak load times. The data represents real residential demand trends, guaranteeing that simulation outcomes are based on household behavior. In this model, the load levels of the MSR will represent for 100 percent the demand of households.

To model the load profile of the Monnickendam MSR, this study assumes that the distribution station supplying electricity to small-scale connections represents exclusively households and that energy distribution occurs evenly across all connections. Given that the MSR is connected to 3,276 small-scale consumption connections, the total electricity load is distributed among these households.

The analysis considers two scenarios: 2024 and 2030. The year 2024 represents the current situation, while 2030 is chosen to represent the future scenario, given that grid expansion is expected to remain incomplete until at least the first quarter of 2030, necessitating interim congestion management strategies.

Figure 3.3 illustrates the annual load profile, highlighting seasonal variations in which energy consumption increases during winter, while excess energy is fed back into the grid during summer.

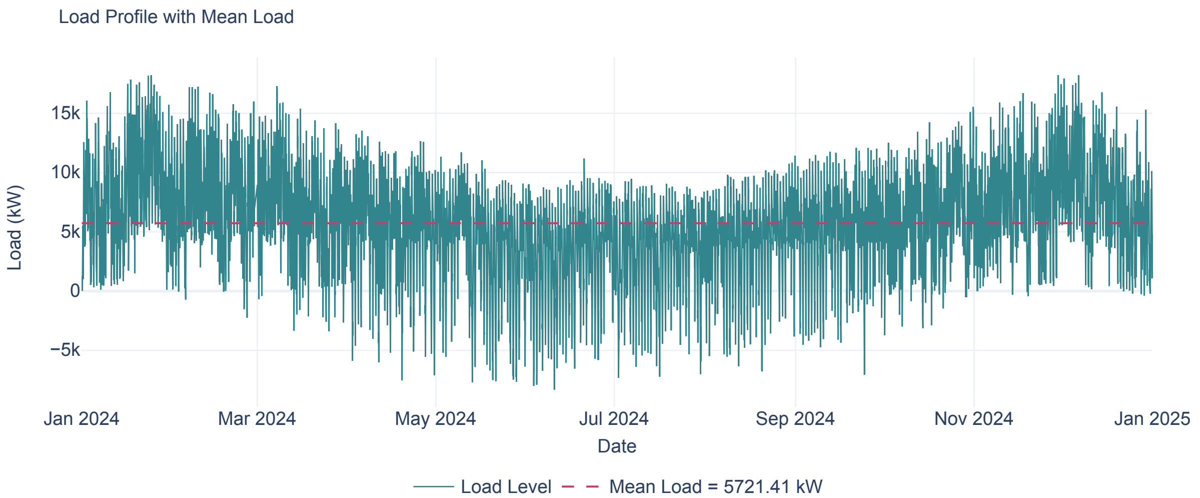


Figure 3.3: Load profile with mean load.

3. Generators

   To meet demand, electricity must be produced by generators. In this research, electricity is generated from generators representing the day-ahead market and imbalance market. For the model, the generators are seen as one generator, where the marginal costs are set by the market prices. As mentioned, the data are retrieved from ENTSO-E. An API is used to easily retrieve hourly prices for one year. First of all, the day-ahead prices are used in the model to research the behavior of R-BESS and the impact on the grid. A second generator is introduced to represent the imbalance market. To model the charging and discharging behavior of R-BESS, a negative generator is implemented to take electricity from the grid, which is fed in by R-BESS. The electricity price which the battery receives is also set to the market price.

   Moreover, a PV generator is included to represent the generation of households. This generator also provides a way to research different weather conditions. To estimate the installed PV capacity for Monnickendam, the following calculation was applied. The Monnickendam MSR serves 3,276 households. Based on national averages, Dutch households typically have 7.35 solar panels per household, derived from an average of 3.5 panels per person and an average household size of 2.1 persons (Centraal Bureau voor de Statistiek (CBS), 2024; Netbeheer Nederland, 2024b). This results in an estimated total of approximately 24,078 solar panels installed across the service area. Assuming a standard panel capacity of 400 Wp (0.4 kW), the total installed PV capacity is estimated to be 24,078 panels multiplied by 0.4 kW per panel, yielding approximately 9.63 MW of installed PV capacity.

4. Store

   In this model, household energy storage is represented as a unified store component, constrained by parameters such as capacity, charge rate, discharge rate, and efficiency losses. A store component is selected to model the aggregated BESS of households, with charging and discharging rates implemented through links. The total battery capacity is allocated across different operational strategies: arbitrage, self-sufficiency, and participation in balancing markets.

   Self-sufficiency refers to the storage of solar energy to use at a later moment in time, potentially reducing the reliance on the grid. The specific scenarios and their implementation details will be elaborated upon in the implementation phase of this study.

   The baseline scenario is determined based on the current and projected installed power capacity of R-BESS in the Netherlands. According to TenneT (2024b), the installed power of household batteries is 2.1 GW, with an expected increase to 4.4 GW by 2030. To scale this to Monnickendam, the following approach is applied:

   (a) The number of small-scale household electricity connections in Monnickendam is 3,276.

(b) The total number of households in the Netherlands is currently 8,300,000 and projected to reach 8,660,000 by 2030 (Centraal Bureau voor de Statistiek (CBS), 2024).

(c) The proportion of Monnickendam's households relative to the national total results in the corresponding R-BESS power for Monnickendam of 0.8289 MW for 2024 and 1.7366 MW for 2030. It is assumed that the number of households in Monnickendam scales with the national prognosis of the amount of households.

In this study, lithium-ion batteries (LIBs) are selected as the storage technology because of their technical and market advantages. LIBs offer a high round-trip efficiency of 90–100% and a relatively high energy density, making them suitable for residential applications where space and efficiency are critical factors (Ferreira et al., 2013; Hall & Bain, 2008). In addition, their low self-discharge rate and high reliability enable effective storage of electricity over extended periods (Zubi et al., 2018). Furthermore, LIBs currently represent the dominant battery technology in the market and continue to attract the largest share of investment in the energy storage sector, a trend expected to persist through at least the end of 2025 (Pillot, 2017). For these reasons, LIBs are adopted in this research as the baseline technology for R-BESS.

To determine total storage capacity, the estimated average duration of household battery operation is considered, with LIBS averaging 4.2 hours (Lazard, 2024). Charge and discharge efficiencies are also based on annual figures reported by Lazard, ensuring consistency with industry benchmarks.

5. Links

Electricity is transported through transmission links that connect the MSR to MV/LV stations and subsequently to households. These transmission lines are modelled as alternating current lines, taking into account resistance, reactance, and maximum capacity. This is essential for accurately modelling grid losses and voltage drops and analyzing the impact of network constraints on energy distribution. As mentioned, the costs of the different energy markets are set as marginal costs on the links between the generators and the grid node.

Lastly, energy taxation is another relevant economic component that needs to be included in the model. According to the Dutch tax authorities, the energy tax rate for electricity is set at €0.10154 per kWh, and this amount is further increased by a VAT of 21%, resulting in a total effective energy tax of €0.12286 per kWh (Belastingdienst, 2024). Incorporating this taxation into the model adds an additional economic dimension, influencing the optimal use of energy storage and trading strategies. These tax costs are implemented as marginal costs on the link between the MSR and the household bus. Additionally, due to the current net metering policy, energy fed back into the grid from household PV systems is compensated at the retail rate, effectively offsetting the energy tax. To reflect this in the model, the marginal cost on the MSR-to-household link is set to minus the energy tax for PV-generated electricity. However, this adjustment is removed in the 2030 scenarios, as the net metering scheme is scheduled to be phased out by that time (Ministry of Economic Affairs and Climate, 2025b).

Market prices

For modelling the different strategies of R-BESS, data is needed from different markets. Therefore, data are retrieved from the day-ahead market and imbalance market.

To assess the arbitrage potential of R-BESS, the day-ahead market prices of the Dutch electricity spot market in 2024 are incorporated into the model. These prices, expressed in euros per megawatt hour (€/MWh), have an hourly resolution and will therefore be scaled to a 15-minute resolution. The day-ahead market is a central platform where electricity is traded one day before actual delivery, with prices determined for each individual hour. Every day at noon, market participants submit bids to buy or sell electricity for the 24 hours of the following day. A European auction mechanism matches supply and demand, resulting in a single clearing price per hour for each bidding zone. In this model, the day-ahead prices are used as a baseline revenue stream for the battery system. Batteries are assumed to charge during low-price hours and discharge when prices are high, in order to maximize arbitrage opportunities. This setup allows for an assessment of how batteries can generate value through price volatility.

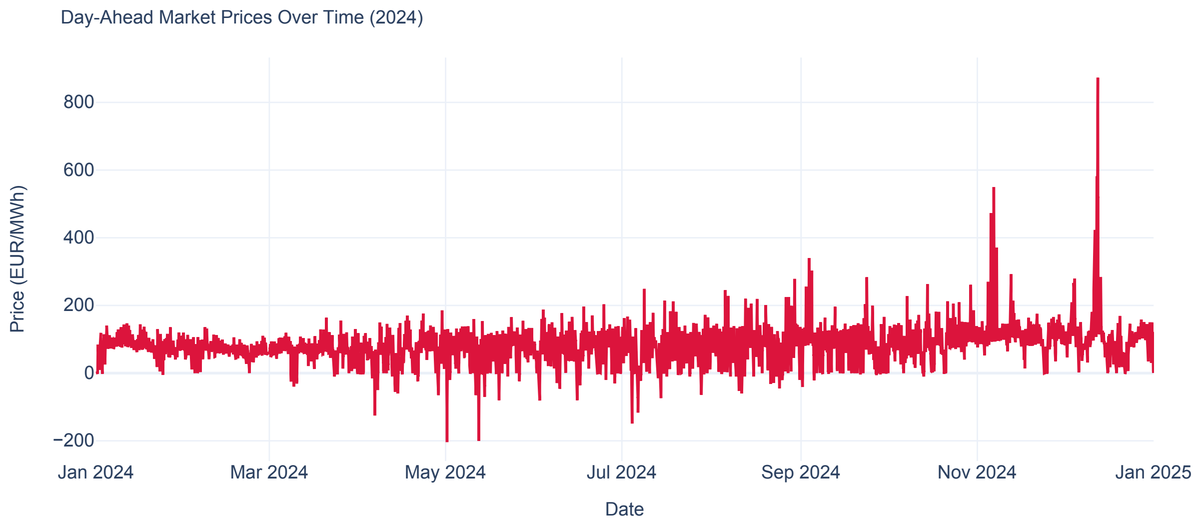


Figure 3.4: Day-ahead market prices over time.

Moreover, to replicate battery involvement in the balancing market, imbalance prices are incorporated in a 15-minute interval. These rates are also indicated in €/MWh and reflect the price related to the upward or downward adjustment of electricity. Considering that the imbalance settlement period in the Netherlands lasts 15 minutes, this information enables a detailed depiction of real-time market circumstances, particularly significant for aggregated battery systems reacting to imbalance notifications.

The battery can supply energy during shortages and discharge during moments of over supply (TenneT, 2016). As larger price fluctuations occur in the imbalance market, larger revenues can be earned. However, since TenneT publishes balancing requests every 5 minutes, both moments of shortfall and surplus can occur. This could potentially lower the amount of revenue or even pay suppliers or consumers. As the formulas are important for understanding the imbalance market, but outside of the scope of this research, they are included in the Appendix B.

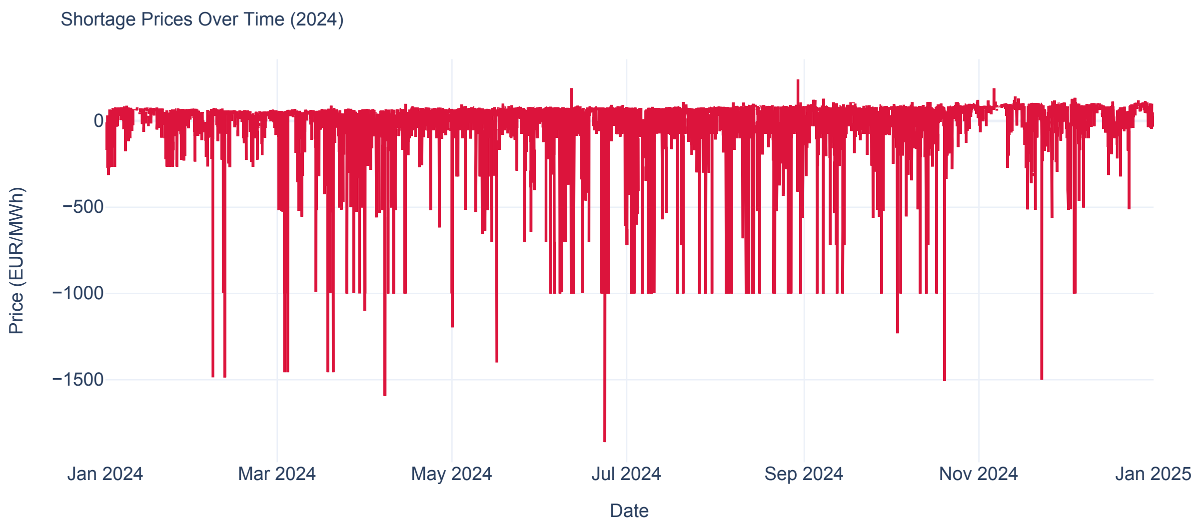


Figure 3.5: Shortage prices over time.

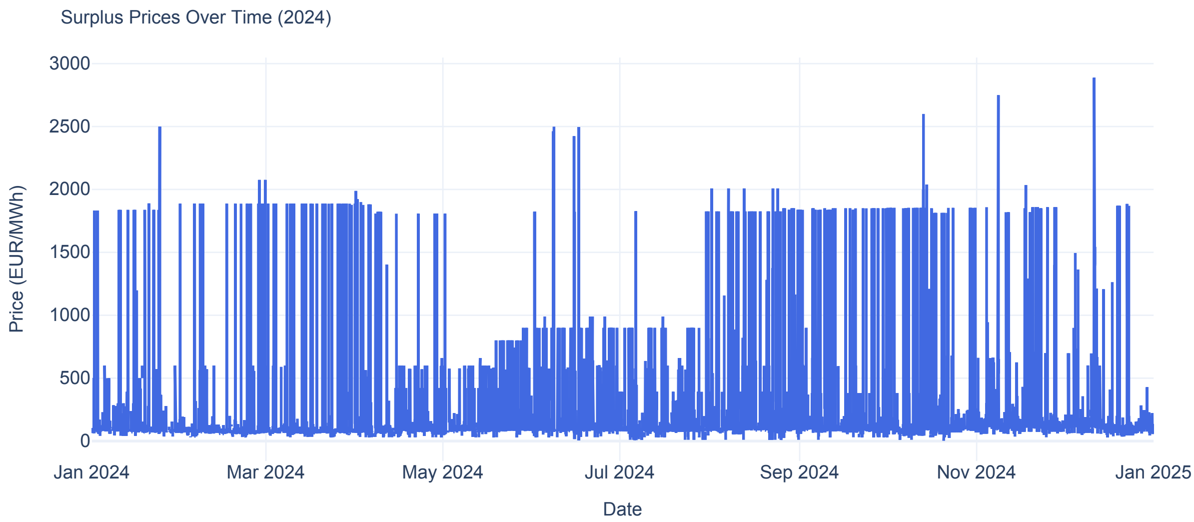


Figure 3.6: Surplus prices over time.

System boundaries

As mentioned above, this research investigates the effects of R-BESS on load levels in the Dutch electricity grid. The MSR Monnickendam is selected as a case study to model these effects. This area is representative of the current challenges related to grid congestion in the Netherlands, as it already experiences net congestion during the winter period. Moreover, data has been obtained from Liander, enabling the use of a real-life case in which the impact of R-BESS can be modelled. The purple area in Figure 3.7 indicates the boundary of the system.

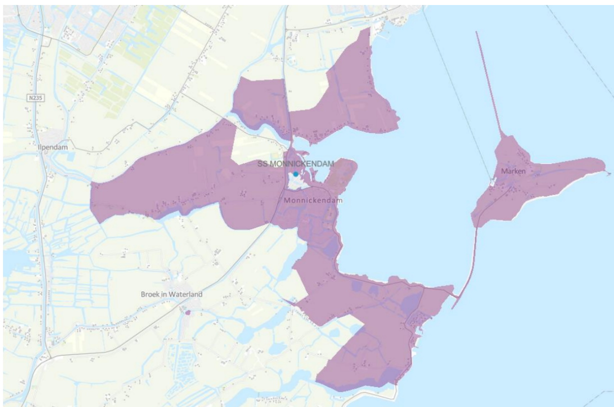


Figure 3.7: The system boundary of this research. The purple area indicates the households connected to the Monnickendam MSR. (Liander, 2023)

Congestion-neutral strategies

To evaluate the impact of R-BESS on congestion under future electricity system configurations, two congestion-neutral strategies were selected: time constraints and ToU tariffs. These strategies were chosen for their complementary characteristics and their potential to influence battery behavior without requiring complex system integration. Time constraints represent a rule-based operational limit, where charging and discharging are restricted during the 12:00-14:00 and 17:00-19:00. This strategy was selected because of the preference of the DSO to achieve congestion-neutrality with time-based constraints. The approach allows for an assessment of how hard limitations affect both grid impact and battery profitability.

ToU tariffs, on the contrary, offer a market-based incentive mechanism. By varying net tariffs across time blocks, this strategy provides an economic signal to steer battery operation away from peak stress periods without enforcing strict behavioral rules. This approach aligns with recent research commissioned by Alliander, in which CE Delft evaluated ToU tariffs as a means to promote grid-friendly behavior while maintaining user flexibility. The net tariffs used are listed in Table 3.2 and are based on research by Berenshot and CE Delft, using the same values (CE Delft, 2024; Berenschot, 2024a).

Together, these two strategies enable a comparative analysis between rule-based and incentive-based interventions. This choice allows for the investigation of trade-offs between grid impact and economic feasibility. Their implementation in this research aligns with the broader objective of exploring scalable and practical approaches for congestion-neutral battery integration.

Table 3.2: Time-of-Use tariffs excluding VAT for winter (October–April) and summer (April–October)

Hour of day	Winter tariff (€/kWh)	Summer tariff (€/kWh)
0	0.14	0.09
1	0.11	0.07
2	0.10	0.06
3	0.09	0.05
4	0.09	0.05
5	0.09	0.05
6	0.11	0.04
7	0.12	0.02
8	0.11	0.00
9	0.08	0.00
10	0.05	0.00
11	0.03	0.00
12	0.03	0.00
13	0.04	0.00
14	0.06	0.00
15	0.11	0.00
16	0.17	0.06
17	0.23	0.13
18	0.24	0.15
19	0.24	0.16
20	0.23	0.16
21	0.21	0.16
22	0.20	0.14
23	0.17	0.12

3.3.4. Formalization

During the formalization phase, the conceptual model of congestion-neutral R-BESS is converted into a mathematical optimization framework. A framework which can be integrated into the PyPSA package. This model aims to assess the impact on load levels and economic performance of household batteries operating without constraints and under congestion limits.

This stage emphasizes the establishment of the objective function and the description of the system constraints that direct the optimization process. The aim is to first replicate R-BESS performance in the current environment to answer the second subquestion. Afterwards, batteries are modelled with congestion-neutral strategies and parameter uncertainty to answer the third subquestion. Parameter uncertainty will be elaborated in the usage phase. The optimization challenge seeks to minimize system costs while enhancing the net income from battery operations by modelling involvement in both the day-ahead and imbalance markets. Overall, this section will cover two parts:

1. The modelling objective: The objective function for the model used in this research is described.

2. Constraints: The constraints for optimizing the objective function are covered mathematically in this section.

Modelling objective

The modelling objective of the PyPSA model is to minimize the total system costs. This includes generation, storage, and transmission costs. A simplified version of the objective function from Brown et al. (2018) includes:

$$\min \mathcal{C}_{\text{total}} = \sum_{t \in T} \left(C_t^{\text{gen}} + C_t^{\text{trans}} + C_t^{\text{stor}} \right) \tag{3.1}$$

Where:

- C_t^{gen} is the total generation cost at time step t, in this case the price of the day-ahead or imbalance market.
- C_t^{trans} is the total cost of the transmission investment in the time step t, based on the energy tax that is allocated on the MSR to the household link.
- C_t^{stor} is the total storage cost at time step t, including variable costs for charging and discharging.

Energy flow balances

To ensure a physically realistic and stable electricity system, PyPSA includes energy flow balancing constraints based on the principles of energy conservation and Kirchhoff's laws. These constraints are enforced at every node and time step in the network.

The power balance constraint ensures that electricity supply equals demand at each node, accounting for generation, charging, and discharging of storage systems, and electricity demand.

$$\sum_s g_{n,s,t} + \sum_s h_{n,s,t} - \sum_s f_{n,s,t} = \sum_s d_{n,s,t} \quad \forall n, t \tag{3.2}$$

Where:

- $g_{n,s,t}$: Generation at node n, from generator s and time t
- $h_{n,s,t}$: Storage discharging to the grid (output from store s)
- $f_{n,s,t}$: Storage charging from the grid (input into store s)
- $d_{n,s,t}$: Demand at node n, for household s, at time t

In an electricity network, Kirchhoff's voltage law ensures that the sum of voltage differences around any closed cycle in the network is zero. This constraint governs how electricity flows across lines in a looped system.

$$\sum_{l \in c} x_l f_{l,t} = 0 \quad \forall c, t \tag{3.3}$$

Where:

- c: A closed cycle (loop) in the network
- x_l: Reactance of line l
- $f_{l,t}$: Power flow on line l at time t

These energy balancing constraints are built into the PyPSA framework to ensure physically feasible and optimized power system operation.

Generator constraints

To guarantee that electricity demand is met and that the R-BESS can participate in the electricity market, two types of generators are required. First of all, a generator is needed to supply the electricity demand of households. In this case, the generator will meet demand at day-ahead price.

Moreover, a negative generator is included in the model to absorb an energy surplus caused by R-BESS. This constraint ensures dispatch is non-positive and does not exceed charging limits. A negative generator facilitates maximizing revenue of R-BESS while confirming to the objective function. The constraints can be found in equation 3.4 and 3.5.

$$0 \leq g_{n,s,t} \leq G_{n,s} \quad \text{for positive generators} \quad \forall\, n, s, t \tag{3.4}$$

Where:

- $g_{n,s,t}$ is the dispatch (in MW) of positive generator s at bus n and time t.
- $G_{n,s}$ is the nominal installed capacity (in MW) of positive generator s at bus n.

$$-G_{n,s} \leq g_{n,s,t} \leq 0 \quad \text{for negative generators (e.g. electricity feed-in)} \quad \forall\, n, s, t \tag{3.5}$$

Where:

- $g_{n,s,t}$ is the dispatch (in MW) of negative generator s at bus n and time t.
- $G_{n,s}$ is the maximum charging power capacity (in MW) of the battery unit at bus n.

Store constraints

To ensure realistic operation of the R-BESS, a store constraint is implemented that governs the energy flow of the battery. These constraints account for charging and discharging through associated links, as well as standing losses over time. The standing loss simulates inefficiencies or self-discharge of the storage unit.

The energy balance of the store is given in Equation 3.6:

$$e_{n,s,t+1} = \eta_s \cdot e_{n,s,t} + \Delta t \cdot (p^{\text{in}} n, s, t - p^{\text{out}} n, s, t) \quad \forall, n, s, t \tag{3.6}$$

Subject to the following bounds:

$$0 \leq e_{n,s,t} \leq E_{n,s} \quad \forall, n, s, t \tag{3.7}$$

Where:

- $e_{n,s,t}$ is the state of charge (in MWh) of store s at node n and time t.
- $E_{n,s}$ is the energy capacity (in MWh) of the store.
- η_s is the standing loss factor per time step.
- $p^{\text{in}} n, s, t$ is the charging power (in MW) entering the store via the associated link.
- $p^{\text{out}} n, s, t$ is the discharging power (in MW) leaving the store via the associated link.
- Δt is the duration of the time step (per 15 minutes).

Charge and discharging constraints

Additionally, further constraints are necessary for the charging and discharging links. The link capacity is the maximum of the power of the battery and the actual feed-in to the store component depends on the efficiency of the links. The constraints are shown in the following equations:

$$0 \leq p^{\text{in}}_{n,s,t} \leq P_{n,s} \quad \forall n, s, t \tag{3.8}$$

The storage charging power $p^{\text{in}}_{n,s,t}$ describes the power flow from the household to the store component via the link. When reduced by the charging efficiency η^{charge}_{s}, it results in the effective power that increases the storage energy level over time.

- $P_{n,s}$ is the installed power capacity (MW) of the storage unit.
- η^{charge}_{s} is the charging efficiency.

$$0 \leq p^{\text{out}}_{n,s,t} \leq P_{n,s} \quad \forall n, s, t \tag{3.9}$$

The storage discharge power $p^{\text{out}}_{n,s,t}$ represents the power delivered to the grid from the discharging component. Before reaching the grid, this power is reduced by the discharging efficiency $\eta^{\text{discharge}}_{s}$, representing the actual decrease in storage energy.

- $P_{n,s}$ is the installed power capacity (MW) of the storage unit.
- $\eta^{\text{discharge}}_{s}$ is the discharging efficiency.

As mentioned, load cycling can occur in several energy system models. To prevent this, a constraint is introduced that forbids simultaneous charging and discharging.

$$z^{\text{charge}}_{n,s,t} + z^{\text{discharge}}_{n,s,t} \;\leq\; 1 \quad \forall n, s, t \tag{3.10}$$

Where:

- $z^{\text{charge}}_{n,s,t}$, $z^{\text{discharge}}_{n,s,t} \in \{0, 1\}$ are binary status variables that indicate whether the battery is charging or discharging (1 = active, 0 = inactive).

The constraint in (3.10) ensures that charging and discharging cannot occur simultaneously and therefore prevents load cycling. Whenever the battery is 'on' in either mode, its corresponding variable z takes the value 1.

Congestion-neutral constraints

Battery behavior is prohibited during defined congestion windows to maintain system neutrality.

$$p^{\text{in}}_{n,s,t} \;=\; 0 \quad \forall n, s,\; t \in \mathcal{T}^{\text{block}} \tag{3.11}$$

Where:

- $\mathcal{T}^{\text{block}}$: Set of time periods during which charging is prohibited, defined as $\{\, t \mid 12 \leq \tau(t) < 14\} \cup \{\, t \mid 17 \leq \tau(t) < 19\}$.

This includes all periods t whose hour $\tau(t)$ is at least 12 and before 14 (that is, the interval 12-14:00), plus all periods t whose hour $\tau(t)$ is at least 17 and before 19 (that is, the interval 17:00-19:00).

3.3.5. Implementation

The implementation phase builds on the outcomes of the conceptualization and formalization stages by translating them into model-based scenarios. With the objective function, system components, and relevant constraints defined, a set of scenarios is developed to address subquestions 2 and 3. These subquestions investigate (2) the impact of different household BESS applications on grid performance and economic feasibility, and (3) the effects of integrating congestion-neutral strategies, including an assessment of the robustness of the scenario. Overall, this section will cover how the model is implemented and validated in PyPSA, which scenarios are modelled, which scenarios are used to plot and show in the results section. Furthermore, the method for calculating the grid impact and economic feasibility parameters is described. Last but not least, the rolling horizon optimization output is explained to justify perfect foresight optimization in this research.

Network

While the network itself is shown in Figure 3.2, this input-output model illustrates how the network is used and optimized within the simulation process. Input variables (green) define the conditions under which the network is constructed and combined with scenario variables (blue). The resulting scenarios are optimized using a MILP that determines the optimal power flow from the grid through the MSR to the household. As illustrated in the figure, every scenario will be optimized separately, resulting in the output variables. This optimization aims to minimize total system costs associated with serving demand and trading with the the R-BESS. Output variables (orange) reflect the charging behavior, congestion impacts, and system-level costs.

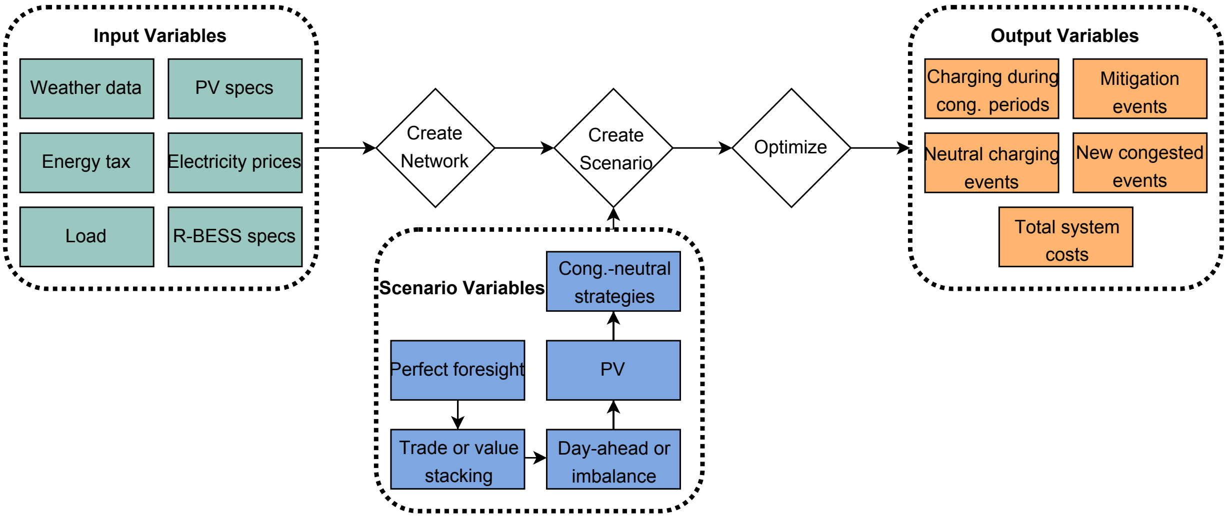


Figure 3.8: Conceptual structure of the optimization model used in this research.

Validation

To ensure the accuracy and reliability of the modelled R-BESS, this research incorporates a structured validation approach. Validation aims to confirm that the battery behavior aligns with theoretical expectations, known market dynamics, and practical expert insights.

First of all, The battery dispatch behavior will be validated against real-world price signals and established theoretical frameworks. For the day-ahead market, the validation will involve examining if the modelled behavior corresponds with expected economic dispatch principles. The output should represent charging during periods of low prices and discharging during high-price intervals. Similarly, validation in the imbalance market will involve assessing whether the modelled battery dispatch accurately reflects responsiveness to volatile real-time price signals.

Moreover, the modelled battery behavior will be validated by experts from Witteveen+Bos, who conducted research in battery storage systems. Experts will be asked to assess the plausibility of the modelled dispatch patterns based on their practical experience and knowledge from research.

Afterwards, the integrated system behavior, including PV generation will be validated. This involves visualizing and analyzing simulated energy flows between PV generation, battery storage, household consumption, and grid imports. This assessment aims to confirm that the interactions between these system components accurately represent realistic network dynamics.

Lastly, sensitivity and robustness analyses will be performed to evaluate the model's stability under varying assumptions. These analyses will ensure the reliability and consistency of the results, thereby improving the credibility and generalizability of the research findings. This will be explained in more detail in Section 3.3.6.

Scenarios

To create as representative scenarios as possible, the scenarios are based on the literature review and interviews. To create an overview of all scenarios and how they are build upon each other, the scenarios are layered, where the full layering graph can be found in Appendix E. The scenario framework consists of five key layers: foresight, markets, trading or value stacking, PV integration, and congestion-neutral strategies. The first layer distinguishes between perfect foresight and a rolling horizon approach. Under perfect foresight, the model has access to complete data for the entire simulation period, enabling fully informed decisions. In contrast, the rolling horizon limits the optimization to a defined time window and restricts the period over which future data is available, better reflecting real-world decision-making under uncertainty.

The second layer defines the market configuration. Scenarios are structured based on how the available battery capacity is allocated between the day-ahead and imbalance markets. A scenario labeled 100_0 indicates that 100% of the battery is reserved for day-ahead trading, while 0_100 implies exclusive use on the imbalance market. Intermediate configurations are included in 10% increments, ranging from 90_10 10_90.

Once the market distribution is established, the model defines the battery objective, which is informed by stakeholder interviews. Two main operational strategies are identified:

- **Trading:** The battery is used solely for the participation in the energy market.
- **Value stacking:** The battery serves multiple purposes: supplying household demand, storing excess PV generation, and participating in energy trading.

The fourth layer addresses PV integration, where scenarios either include or exclude residential PV systems. The final layer concerns the implementation of congestion-neutral strategies, specifically the application of time constraints or ToU tariffs.

The combination of all these layers results in a large set of potential scenarios. To maintain clarity and focus, a selection was made during the modelling process to retain only the most representative configurations. As shown in Table 3.3, the selected scenarios represent the extreme boundaries of the design space. This decision allows for a clear illustration of the grid impact and economic feasibility across the full spectrum of R-BESS applications, in line with the research objectives. Additionally, by focusing on the most contrasting cases, the effect of congestion-neutral strategies can be more distinctly evaluated.

For the year 2024, both trade and value stacking scenarios are included. This choice is motivated by developments in the residential battery market: for example, Zonneplan only introduced the option to use its battery systems for self-consumption in late 2023. Prior to that, battery use was limited to market trading within their platform. As such, the inclusion of a pure trading scenario remains relevant for the 2024 context. However, several actors emphasized that value stacking is expected to become the only viable business model in the coming years. Therefore, only value stacking scenarios are considered for 2030.

Finally, value stacking is only modelled in combination with PV integration. This decision was informed by the interview with Liander, in which it was stated that the number of households owning a battery without PV is negligible. As a result, modelling value stacking without PV was not considered meaningful for this study.

Parameter calculation

To evaluate the performance of R-BESS systems, this research focuses on two key dimensions: grid impact and economic feasibility.

Grid impact is defined as the extent to which battery behavior contributes to an increase or decrease in the number of congestion periods, assessed on a 15-minute resolution. This is operationalized through the following four metrics:

1. Already congested periods: For each scenario, the number of time steps in which the MSR is already congested is calculated. This is prior to any battery activity. A period is marked as congested if the energy flow from the MSR to the household exceeds the system's capacity during that interval.
2. Charging during already congested periods: This metric counts the number of time steps in which the battery is actively charging while the grid is already experiencing congestion, thereby worsening grid conditions.
3. New congestion periods: These are instances where the energy flow from the MSR does not exceed capacity without battery activity but exceeds the threshold due to charging. This identifies periods in which battery behavior creates new congestion.

Table 3.3: Overview of model scenarios. The grey rows show the only day-ahead scenarios and the white rows show the only imbalance scenarios.

Scenario	PV	Congestion-Neutral Method
2024	–	–
Day-ahead – Trade	✗	✗
Imbalance – Trade	✗	✗
Day-ahead – Trade	✗	Time Constraints
Imbalance – Trade	✗	Time Constraints
Day-ahead – Trade	✗	ToU Tariffs
Imbalance – Trade	✗	ToU Tariffs
Day-ahead – Value Stacking	✓	✗
Imbalance – Value Stacking	✓	✗
Day-ahead – Value Stacking	✓	Time Constraints
Imbalance – Value Stacking	✓	Time Constraints
Day-ahead – Value Stacking	✓	ToU Tariffs
Imbalance – Value Stacking	✓	ToU Tariffs
2030	–	–
Day-ahead – Value Stacking	✓	✗
Imbalance – Value Stacking	✓	✗
Day-ahead – Value Stacking	✓	Time Constraints
Imbalance – Value Stacking	✓	Time Constraints
Day-ahead – Value Stacking	✓	ToU Tariffs
Imbalance – Value Stacking	✓	ToU Tariffs

4. Mitigation of congestion: This reflects the number of periods where, in the absence of battery activity, grid capacity would be exceeded, but discharging the battery reduces the net flow below the congestion threshold, thus relieving pressure on the network.

Economic feasibility is assessed using total system costs. While it would be ideal to calculate direct financial returns from battery operation, a key modelling limitation in PyPSA complicates this. Specifically, the model does not allow precise tracking of whether the energy stored and discharged by the battery originates from PV generation or the grid, which is an essential distinction for accurate profit calculations. However, due to the relatively limited number of components in the model, total system cost remains a meaningful number. From this, general insights into the profitability of the R-BESS system can still be derived.

Rolling horizon

To assess whether the use of perfect foresight in this study could be justified, additional tests were performed using a rolling horizon optimization approach. For the day-ahead market, an optimization was performed using a 24-hour window with a 48-hour rolling horizon, meaning that the optimizer had access to 48 hours of known prices while optimizing for the first 24 hours. The results showed no significant change in battery behavior compared to the perfect foresight case, supporting the validity of the modelling choice for the day-ahead market. For the imbalance market, a rolling horizon of 30-minute optimization steps was tested with a one-hour forecast window. In this case, some differences in battery behavior were observed, particularly due to shorter time resolution and more volatile price dynamics. However, the rolling horizon approach resulted in a substantial increase in computational time. Given these practical limitations and in line with the exploratory scope of this thesis, perfect foresight was used for all scenarios. The plots can be found in Appendix F.1.

3.3.6. Model Usage

With the full set of predefined scenarios implemented, the analysis now advances to a more in-depth exploration of uncertainty. While the initial phase focused on comparing scenario outcomes under fixed assumptions, the next step addresses how these results may shift under changing system conditions.

Uncertainty is an inherent characteristic of energy system models. It arises from limited knowledge of future demand, technology costs, market behavior, and policy developments (Pfenninger et al., 2014; Neumann and Brown, 2021). Ignoring these uncertainties can lead to misleading conclusions and overconfidence in the model outputs.

To address this, the following sections introduce two complementary approaches: sensitivity analysis to examine the influence of key parameters and robustness to test if the output of the model is generalizable to other MSRs.

Sensitivity analysis

In energy system modelling, sensitivity analysis is essential for understanding how uncertainties in model inputs affect the results. These uncertainties can be parametric, meaning that they relate to uncertainty in the values of input parameters (such as technology costs or system capacities), or structural, meaning they relate to the way the model itself is built. An example is which equations or assumptions are used to represent system behavior (Yue et al., 2018).

A widely used approach to investigate such uncertainties is Global Sensitivity Analysis (GSA). GSA examines how changes in many input parameters, either individually or in combination, influence model output. It allows for the identification of the most influential parameters and helps ensure that the scenario design captures the full range of relevant outcomes. GSA can also be used to test alternative model structures and assumptions, making it a powerful tool for exploring both parametric and structural uncertainty (Moret et al., 2017; DeCarolis et al., 2017). However, applying GSA can quickly become computationally intensive, especially in models with many input variables or long simulation times (Yue et al., 2018). To keep the analysis tractable while still gaining insight into key parameter sensitivities, this study uses a more straightforward method: One-at-a-Time (OAT) sampling.

In OAT sampling, one parameter is varied at a time, while all others are kept constant. This allows the effect of each parameter to be isolated and assessed independently. Although OAT does not capture interactions between parameters as GSA does, it provides a practical and interpretable way to assess the influence of individual parameters without overwhelming computational resources (Saltelli et al., 2008). For this reason, the OAT is used in this thesis to explore how key modelling assumptions affect the results.

Parameter selection

To assess the robustness of the model results, a set of key parameters was selected for sensitivity analysis. These parameters were chosen based on their influence on system performance and the degree of uncertainty associated with their estimation. For solar panel and battery penetration, national installation figures for residential batteries in the Netherlands in 2024 were used. These totals were scaled down to reflect the local context of Monnickendam, assuming a proportional distribution based on population size. This approach ensures that model inputs remain realistic and location-specific while grounded in verifiable national data. For energy taxation, the electricity tax applicable in 2024 was applied. As energy tax directly affects the economic return of residential battery use, particularly under value stacking, it was included as a key parameter.

The sensitivity analysis was performed only for the 2024 scenarios. This decision was based on the greater reliability of short-term assumptions (e.g., technology costs, taxation rates, and deployment figures). In contrast, parameter uncertainty for 2030 is significantly higher and would introduce speculative variability into the analysis. Each selected parameter was varied from 0% to 200% of its base value, in increments of 25%. This range is designed to capture both low- and high-end sensitivity scenarios: 0% reflects full removal of the parameter (e.g., no batteries or PV), 100% represents the base case and 200% reflects a high-adoption or high-cost scenario. These stepwise increments allow for a structured exploration of parameter influence.

The same reasoning is used for the energy tax. As the energy tax ranges between 0.036 €/kWh and 0.12 €/kWh in the last 15 years exclusive VAT, a boundary of 0% and 200% will cover the uncertainty in the energy tax.

An overview of the parameters tested and their classification as parametric or structural uncertainty is provided in Table 3.4. Parameters are considered parametric if they relate to input values (e.g., number of batteries), and structural if they relate to the way the system is modelled (e.g., demand profiles).

Parameter	Description	Type of Uncertainty
Battery penetration	Scaled number of residential batteries	Parametric
PV penetration	Local PV adoption in Monnickendam	Parametric
Energy tax	Household electricity tariff (2024)	Parametric

Table 3.4: Overview of sensitivity analysis parameters and their uncertainty classification.

Robustness analysis

To analyze the system in more detail and to assess information about the robustness of our system, the fixed design will be tested under out-of-sample conditions. Out-of-sampling can be used to test how robust the model is and therefore if it is generalizable (McCracken, 2000). In this case, generalizability refers to whether the outcomes of the model can be applied to other MSRs, or whether analysis must be tailored to each specific MSRs.

The performance of the model is tested on the same scenarios as with the sensitivity analysis. In total, the analysis includes weather years from 2015-2024 and in 4 different load levels. The weather years are chosen to check the impact of different weather conditions on the model output. 4 different load levels to assess the impact of different MSR conditions. The load levels of Monnickendam and three other load levels of an MSR are used. As the load levels are higher in comparison with the load levels of the base scenario Monnickendam, battery capacity and PV capacity are scaled to the new load levels to represent the same system. Based on the out-of-sample testing of the selected representative design options, we present their performance in a probabilistic way that reflects the uncertainty of future conditions. By varying household demand levels, the goal is to assess how representative the results from Monnickendam are for other MSRs. Since load profiles influence system behavior structurally, this test supports evaluating the generalizability of the model.

The variation of load and weather conditions is based on the Gaussian distribution. This analysis is explained by Guo et al. (2019), in which the uncertainty description is shown based on probability distributions. This approach is adapted to this research, in which probability distributions will be shown for the amount of mitigation periods and for new plus charging during already congested periods for all out-of-sample conditions.

4

Results

In this chapter, the modelling results are presented. These simulations are designed to answer the second and third subquestion, which evaluate the impact of different R-BESS applications and congestion-neutral strategies on grid performance and economic feasibility. As a result of the large number of outcomes, this section focuses on representative cases. This chapter will focus on both trading and value stacking scenarios for 2024 and will shift towards only value stacking scenarios in 2030. Within those scenarios, three different networks are simulated. The first network is focused on non-constricted battery behavior. The second one is focused on time constraints, and the last network includes ToU tariffs. This section presents the quantitative results and addresses the second and third subquestion:

Q2: *What is the impact of different R-BESS applications on grid performance and economic feasibility?*
Q3: *What is the impact of integrating congestion-neutral strategies on grid performance and economic feasibility, and how robust are the results?*

4.1. Battery Behavior Validation

Before analyzing the grid impact of the R-BESS it is essential to validate that the battery behavior in the model corresponds to theoretical expectations and known market dynamics. This section evaluates how the simulated batteries respond to price signals, and if this behavior is valid. The validation will be performed by comparing the performance with the market signals and by validating the output with experts of Witteveen+Bos.

4.1.1. R-BESS Behavior in the Day-Ahead Market

Figure 4.1 shows battery operation with hourly day-ahead market prices, which are scaled to 15 minutes to correspond with the imbalance market and the demand. The behavior is consistent with the economic dispatch logic: the battery charges during low-price hours, shown by the pink bars, and discharges during high-price hours, which are shown in blue. Due to perfect foresight, the R-BESS waits for the absolute minimum price to charge and waits for the absolute maximum to discharge. This enables the battery to capture the full price spread and maximize arbitrage profit. However, as mentioned in Section 3.3.5, there are no significant differences between optimizing for 24 hours and optimizing with rolling horizon. Therefore, the decision was made to continue with perfect foresight. In particular, two daily low-price windows are observed when the battery charges. First of all, the nighttime window, where low demand and constant generation of energy reduce prices. Moreover, during midday high RES generation results in low energy prices. On the other hand, two recurring high price windows correspond with discharging the battery. A morning peak occurs as households and industries begin their daily activities. Finally, a post-work increase in demand and a decline in solar generation increase energy prices. This behavior is validated by a study from CE Delft and Witteveen+Bos (2023), which also highlights charging during the night and around noon, and discharging in the morning peak and afternoon peak. Moreover, the modelled battery behavior was presented to researchers involved in this specific study. These experts in the field of battery storage confirmed that the behavior is both valid and representative.

This daily pattern reflects the Dutch day-ahead market and confirms that the battery responds optimally to expected price patterns. Moreover, the returning pattern shows that the behavior of R-BESS in the day-ahead market is predictable, which is useful for the upcoming sections.

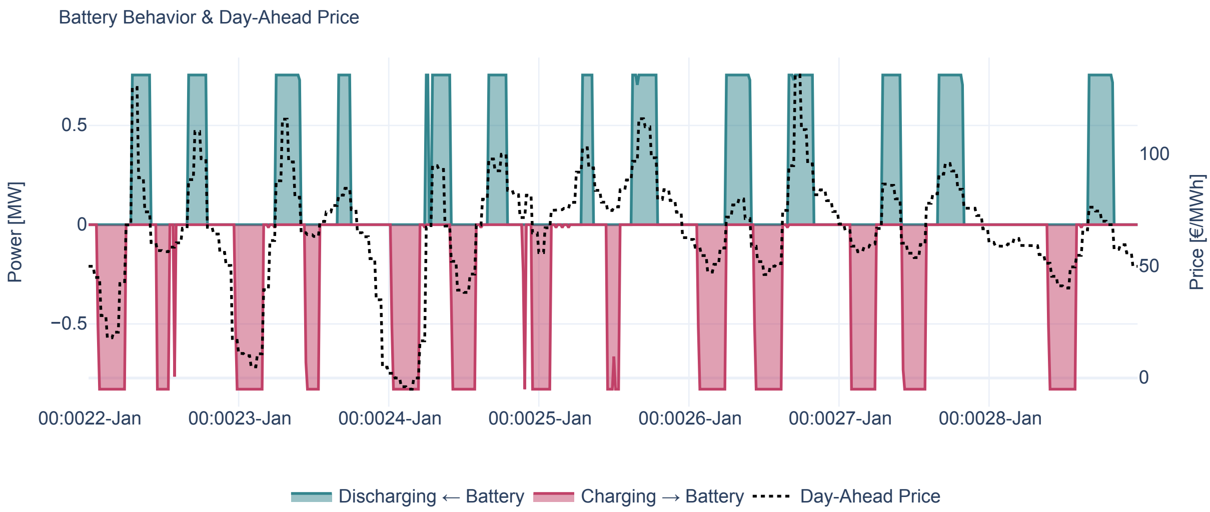


Figure 4.1: Behavior of battery trading in the day-ahead market.

4.1.2. R-BESS Behavior in the Imbalance Market

In addition to the behavior of R-BESS in the day-ahead market, the behavior in the imbalance market should be validated. Figure 4.2 illustrates battery dispatch behavior in the imbalance market, with 15-minute settlement prices. In this scenario, the battery shows a more frequent and short-duration dispatch, reflecting the high volatility of the market. Moreover, it reflects the responsiveness that is required in balancing trading. As prices are set every 15 minutes and the request from the TSO to balance the grid occurs in real-time, a more erratic behavior is as expected. The modelled battery behavior was reviewed by researchers involved in this study, who, as experts in battery storage, confirmed that the simulated behavior is both realistic and representative. Moreover, this battery behavior can be validated by published accounts from R-BESS providers active in the Dutch imbalance market (NextEnergy, 2024; Frank Energie, 2025). These sources indicate that battery dispatch is often not driven by the regular consumption patterns of households or businesses, but rather by less frequent, high-impact imbalance signals from the TSO. As such, the trading behavior reflects a market-driven response to grid-level needs rather than a direct link to daily user demand. The behavior under perfect foresight closely resembles that of rolling horizon optimization, following the same general trend. However, with limited foresight, the battery tends to withhold some capacity for charging and discharging, anticipating future uncertainty. In contrast, the battery with full foresight can optimize its actions more effectively across the entire time horizon. Given the substantial difference in computational time (one large optimization versus approximately 17,000 smaller ones), the decision was made to proceed with the perfect foresight approach.

This behavior demonstrates the battery's attempt to exploit extreme price spikes for charging and discharging. These are common in the imbalance market. However, because of this lower correlation with the typical behavior of energy prices, the imbalance market is more inconsistent than the day-ahead market.

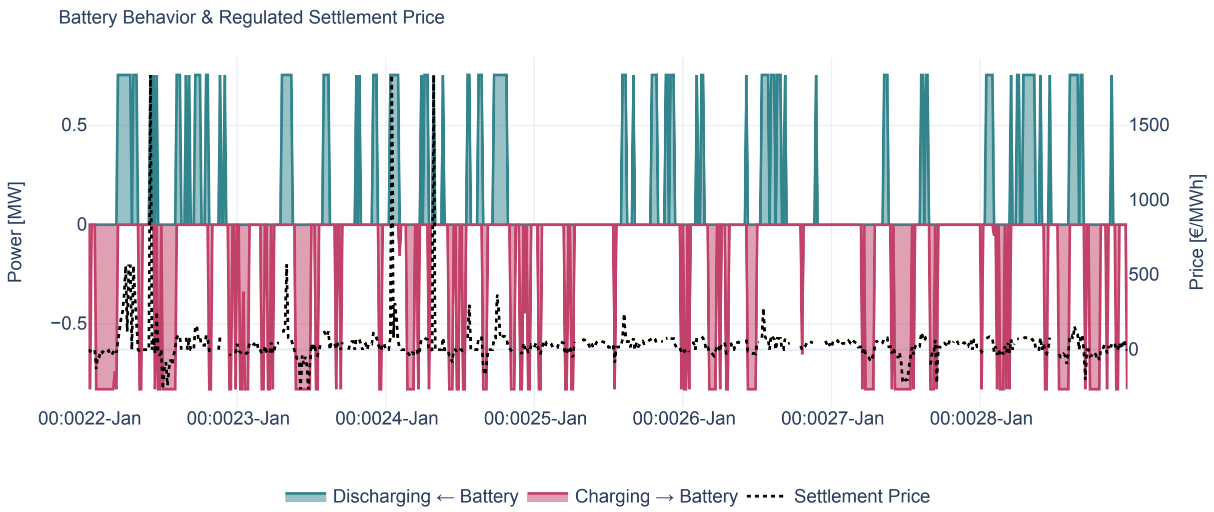


Figure 4.2: Behavior of battery trading in the imbalance market.

4.1.3. R-BESS Behavior including PV

To ensure that the introduction of value stacking is represented correctly in the model, the power flows between PV systems, batteries, and households are visualized. Figure 4.3 illustrates the household-level energy exchanges over a representative week in January.

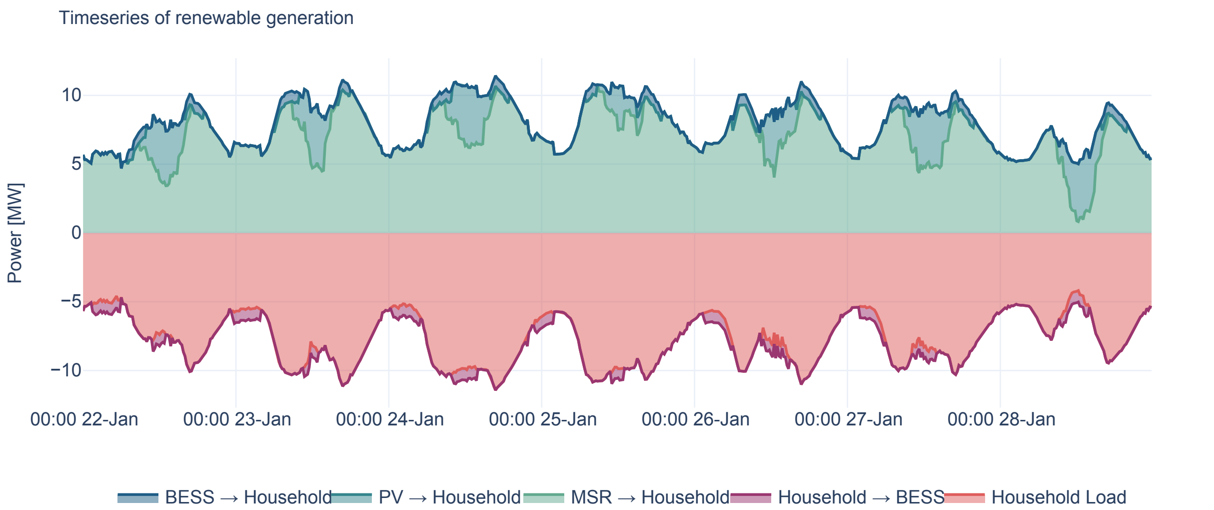


Figure 4.3: Visualization of meeting demand with solar panels, generators and battery discharging.

The stacked area chart confirms that the battery behaves as expected in the value stacking scenarios:

- During periods of high solar PV production (green area), a large share of generation is directly consumed by the household (PV → Household), reducing the need for external imports.
- Surplus PV generation is stored in the battery (Household → BESS, red line) for later use and trading.
- When PV output is insufficient, the battery discharges to cover household demand (BESS → Household, dark blue area), especially during high energy price windows.
- Remaining household demand is met by imports from the main grid (MSR → Household, green area).

In conclusion, the behavior is comparable to real-world behavior and, therefore, can be used for the upcoming scenarios.

4.2. Impact of Energy Trading with Batteries on Grid Load and Economic Feasibility - 2024

The following section introduces several trading scenarios designed to evaluate the impacts of R-BESS on grid congestion on a specific MSR. The modelled scenarios involve trading in the day-ahead and imbalance markets, where different ratios of trading per market are used. The ratios start from 100% day-ahead trading and 0% imbalance trading towards 0% day-ahead trading and 100% imbalance trading in steps of 10%. The scenarios are modelled with perfect foresight to determine the theoretical optimal battery behavior and the corresponding grid impact. Additionally, congestion-neutral strategies are included to research how time constraints and ToU tariffs influence battery behavior grid congestion and economic feasibility. To understand the plots properly, it should be noted that multiple plots in this research use a counter on the y-axis to indicate the frequency of certain events. Each count corresponds to one 15-minute time interval, meaning that a value of 1 on the y-axis represents the event occurring during a single 15-minute period.

4.2.1. Impact of R-BESS on Grid Load

This section explores both seasonal and intra-day patterns in battery operation and its relationship to grid congestion, based on the full set of 2024 simulation results. Although all the modelled trade ratios are part of the simulation, the figures presented here focus on the two extreme scenarios: one in which 100% of battery capacity is allocated to the day-ahead market and another where 100% is reserved for the imbalance market. These scenarios are chosen to highlight the most distinct operational behaviors. The analysis begins with a seasonal overview of congestion occurrences throughout the year, followed by a more detailed examination of time-specific congestion dynamics.

Seasonal behavior

Figure 4.4 shows the sum of monthly congestion occurrences for the full simulation year of 100% day-ahead market trading. There is a clear seasonal trend, with already congested periods peaking in the winter months. This pattern aligns with a higher energy demand driven by heating, shorter daylight hours, and a reduced contribution of solar energy. Notably, these same months show both new congestion and mitigation events. The other months, particularly April through September, show only neutral charging events and are therefore of less interest for the 2024 scenarios. The main reason for this observation is a decrease in demand and an increase in solar generation. Another observation is the dominance of neutral charging throughout the year, indicating that batteries often operate without increasing congestion. This underscores that batteries can trade profitably without harming the grid for most of the year. For 100% imbalance market trading, the same trend is discovered and therefore the plot is placed in Appendix F.3.

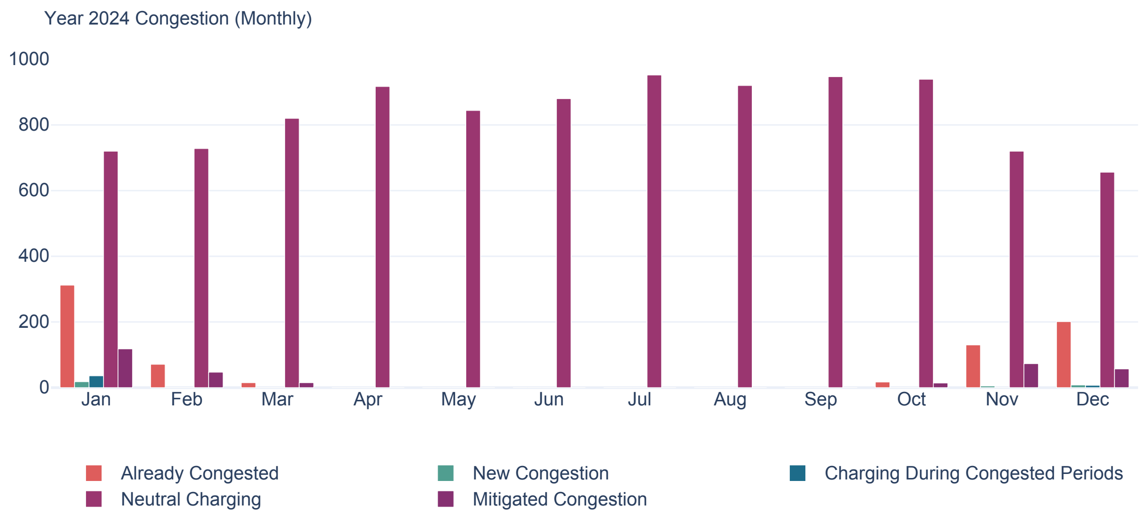


Figure 4.4: Seasonal behavior and grid impact of the R-BESS.

Intra-day patterns in the day-ahead market

After investigating the seasonal pattern of congestion, a more in-depth analysis is needed to understand exactly when the behavior of the battery could result in new congestion periods, charging during already congested periods, or in mitigating congestion.

First of all, battery behaviors that do not result in a different congestion state, but only act neutral or increase already congested periods, are researched. A different congestion state refers to either the mitigation of an existing congestion period or the emergence of a new one. Figure 4.5 confirms that the majority of battery charging occurs during neutral grid conditions, with relatively few instances of charging during congested periods. This is a positive finding, indicating that the battery often operates in a way that does not weaken grid stability, even under unconstrained market access.

However, a cluster of congested charging events is shown around noon. This is driven by the concentration of low prices during the midday hours, which are correlated with high PV output. As a result, batteries are economically incentivized to charge, which may overlap with congestion from excessive solar feed-in. In addition, the battery charges between 07:30 and 08:00, possibly increasing grid congestion.

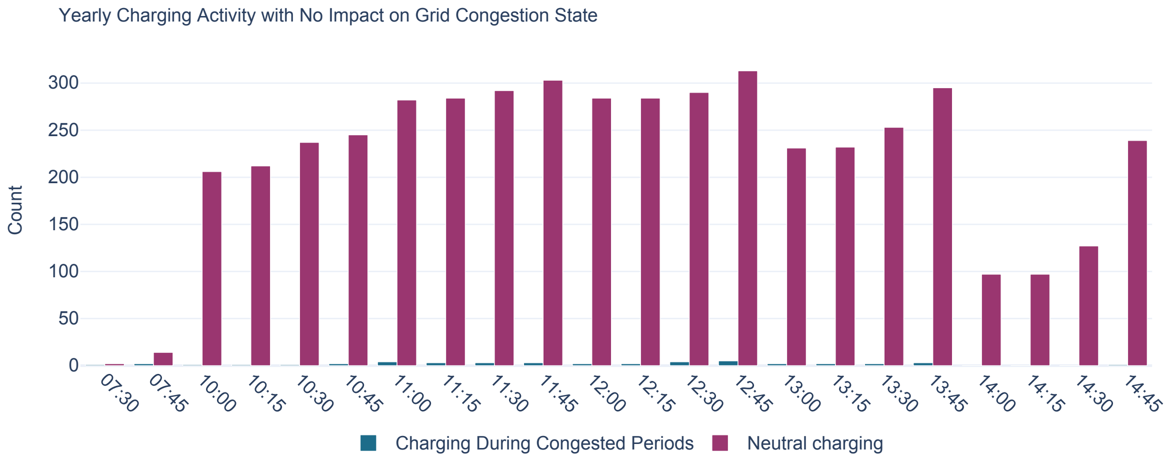


Figure 4.5: Visualization of the charging behavior which occurs during already congested periods or neutral charging periods. This is a close-up view of the data, only the window with charging during already congested periods is shown. See Appendix F.3 for the complete graph.

Figure 4.6 further strengthens the interpretation of daily patterns, showing that congestion usually occurs during the early morning, late afternoon, and evening hours. These congested periods correlates with the residential demand peaks discussed in the validation section, namely the morning ramp-up and the post-work peak. This visualization builds on Figure 4.5, with a focus on events that represent new system developments. Charging during congested periods and neutral charging do not alter the system state. In contrast, newly occurring congestion events and mitigation result in a new situation. The figure shows many periods of congestion mitigation during these periods, which means that batteries are discharged at the right time and contribute to reducing net load. Only a limited number of new congestion events are observed, further validating the benefit of dispatch behavior in the day-ahead market. However, it should be noted that new congested periods, even if they are few, play a key role in the decision-making process of DSOs and the TSO.

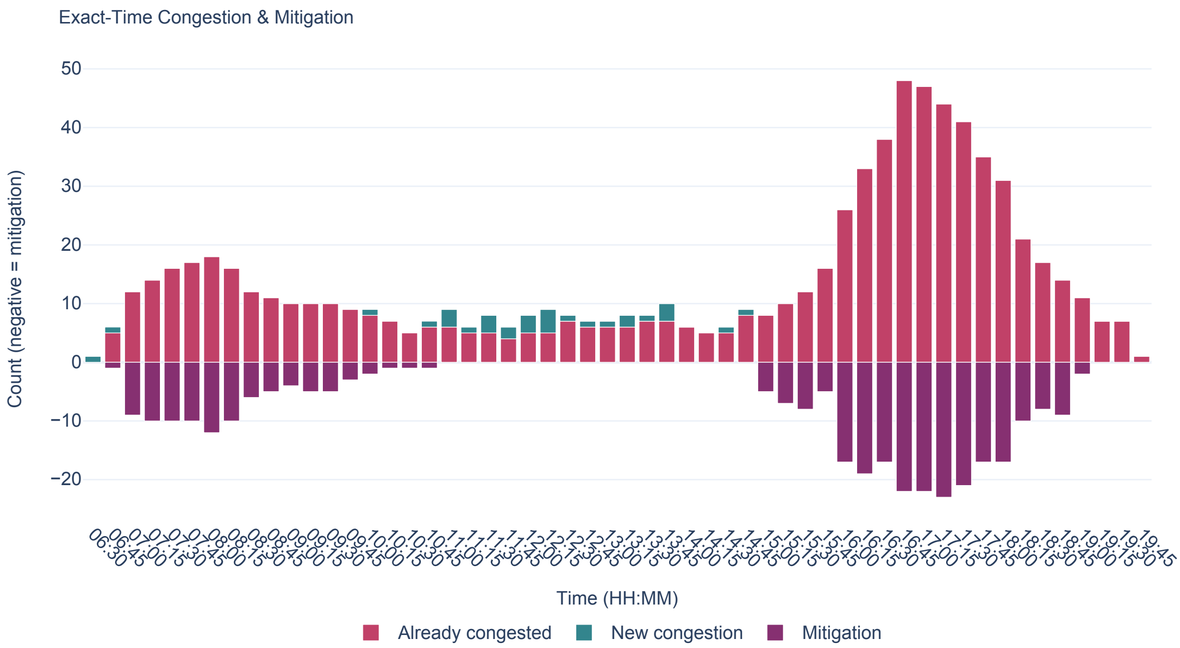


Figure 4.6: Intra-day pattern and grid impact of day-ahead market trading.

Intra-day patterns in the imbalance market

Compared to day-ahead market trading, imbalance trading shows a different behavior. The plot, shown in Figure 4.7, illustrates that even under imbalance trading, a large proportion of charging still occurs under neutral grid conditions. However, imbalance trading results in a larger amount of charging during already congested period and more spread throughout the day. This reflects the volatile and reactive nature of the imbalance market, where price signals change quickly and batteries must respond more dynamically. Congested charging is generally more distributed throughout the day compared to the day-ahead scenario and appears most frequently in the afternoon hours.

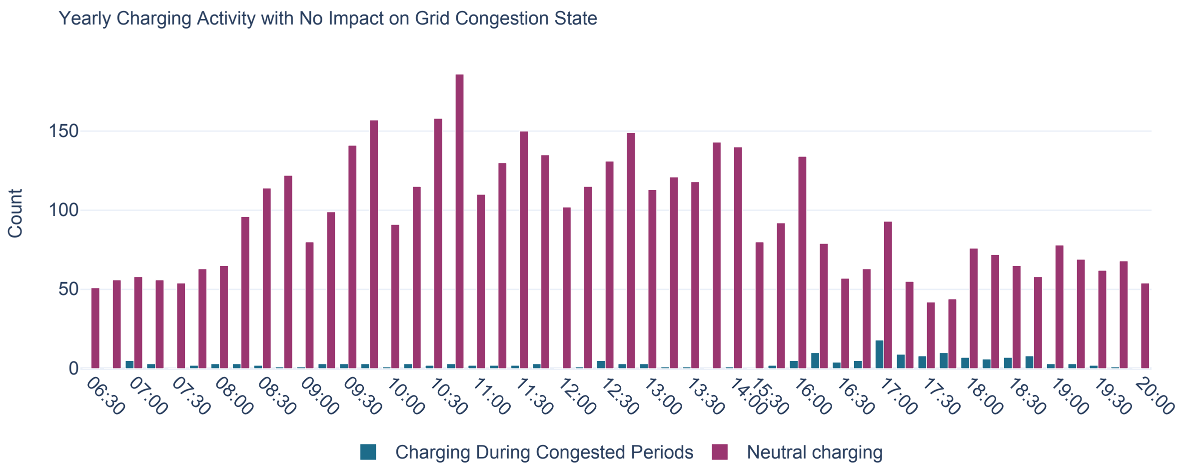


Figure 4.7: Visualization of the charging behavior which occurs during already congested periods or neutral charging periods. This is a close-up view of the data, only the window with charging during already congested periods is shown. See Appendix F.3 for the complete graph.

Figure 4.8 demonstrates the time-specific impact of imbalance trading on congestion. There is a peak in the appearance of congestion in the late afternoon and early evening. Moreover, the increased periods of congestion arise in the complete window of 06:15 until 20:15. This could potentially complicate the process of constraining the battery behavior to specific time frames. However, mitigation effects are also significant. These positive results confirm that even in the imbalance market, batteries can contribute positively to grid management. However, this comes with an increased risk of inadvertently increasing congestion periods. Due to the volatile nature of the imbalance market, less correspondence between market outcomes and local congestion conditions is expected compared to the day-ahead market. This validates existing concerns from DSOs and actors such as Alliander and CE Delft, who indicated that uncoordinated market-based dispatch, especially in the imbalance market, could lead to an increase in congested periods on the grid.

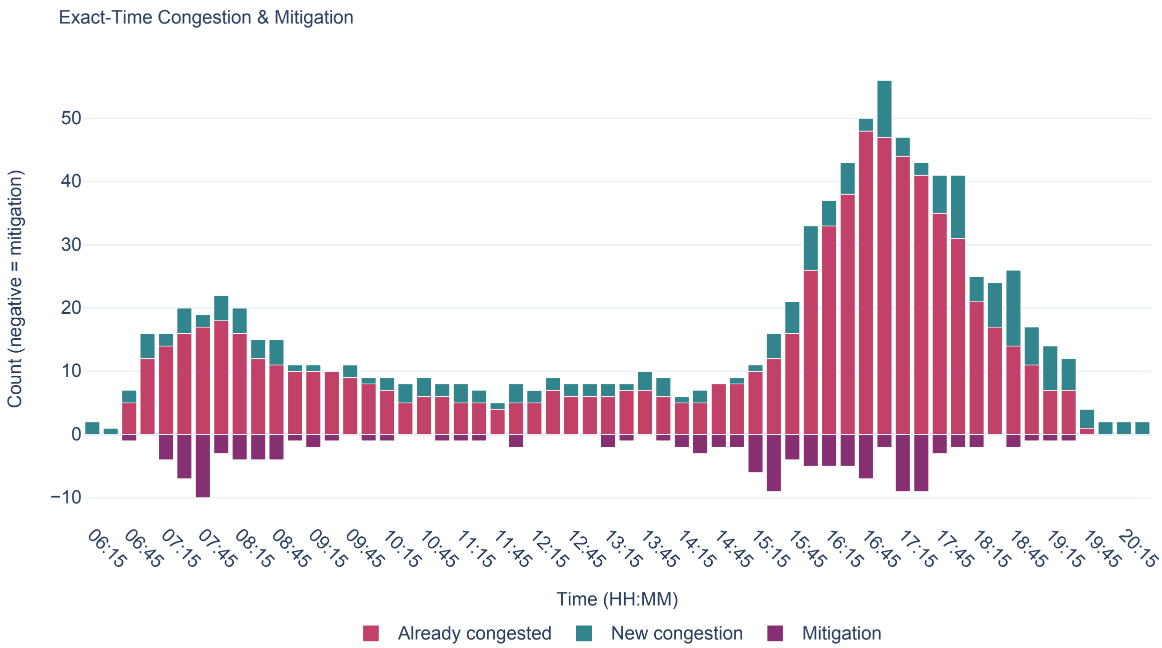


Figure 4.8: Intra-day pattern and grid impact of imbalance market trading.

4.2.2. The Effect of Applying Time Constraints or ToU Tariffs on Grid Load

To assess the influence of congestion-neutral strategies in 2024, both time constraints and ToU tariffs are applied across the full range of day-ahead and imbalance market configurations. The following results explore their impact on congestion metrics, peak shaving, and overall system costs.

Effect on congestion events

Charging during already congested periods (Figure 4.9) increase with a higher imbalance market share. In the 100% day-ahead trading scenario, charging during congestion is limited, but under imbalance operation, the frequency of these events increases considerably. In total, the amount of charging during congested periods increases from 48 to 168. Among the strategies, time constraints are most effective in weakening this behavior, with decreasing 48 to 17 and 168 to 83. ToU tariffs, by contrast, show no significant effect, with 44 and 171 charging during congested periods for, respectively, the day-ahead and imbalance market. This indicates that price signals alone are not sufficient for aggregators to redirect battery operation during congested hours.

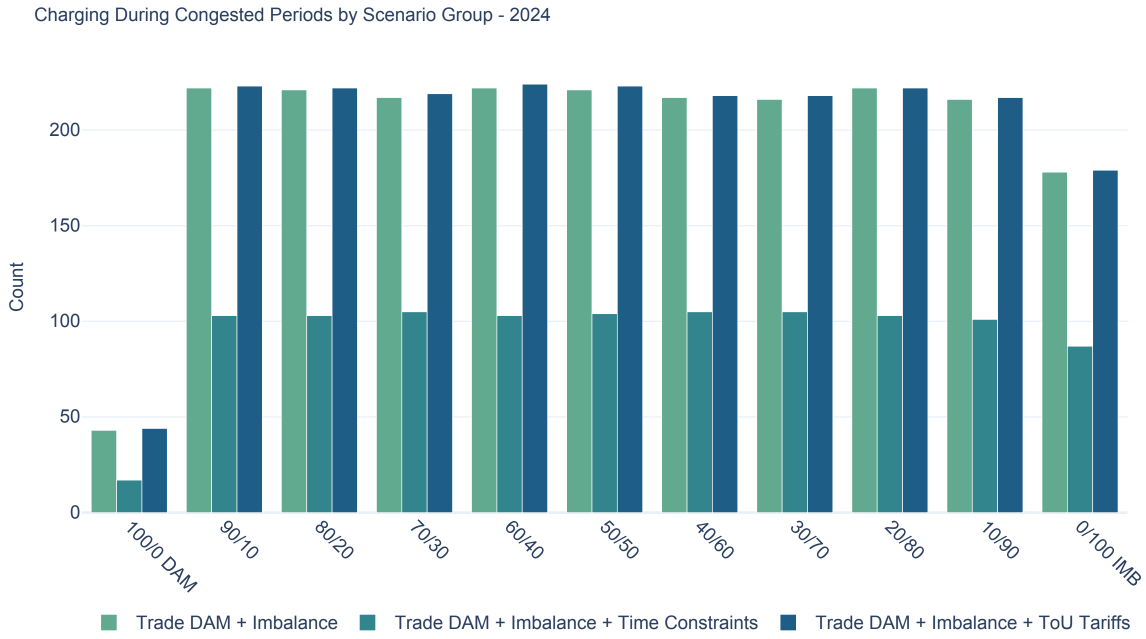


Figure 4.9: Impact of market strategy and congestion-neutral constraints on charging during already congested periods. DAM represents the day-ahead market and IMB represents the imbalance market. These abbreviations will also be used in further plots.

Figure 4.10 illustrates the number of new congestion events, defined as moments when battery activity contributes directly to overload conditions. This metric follows a similar pattern: minimal occurrence in the day-ahead scenarios, increasing sharply with higher imbalance ratios. Again, time constraints significantly reduce these events, while ToU tariffs provide only marginal improvement.

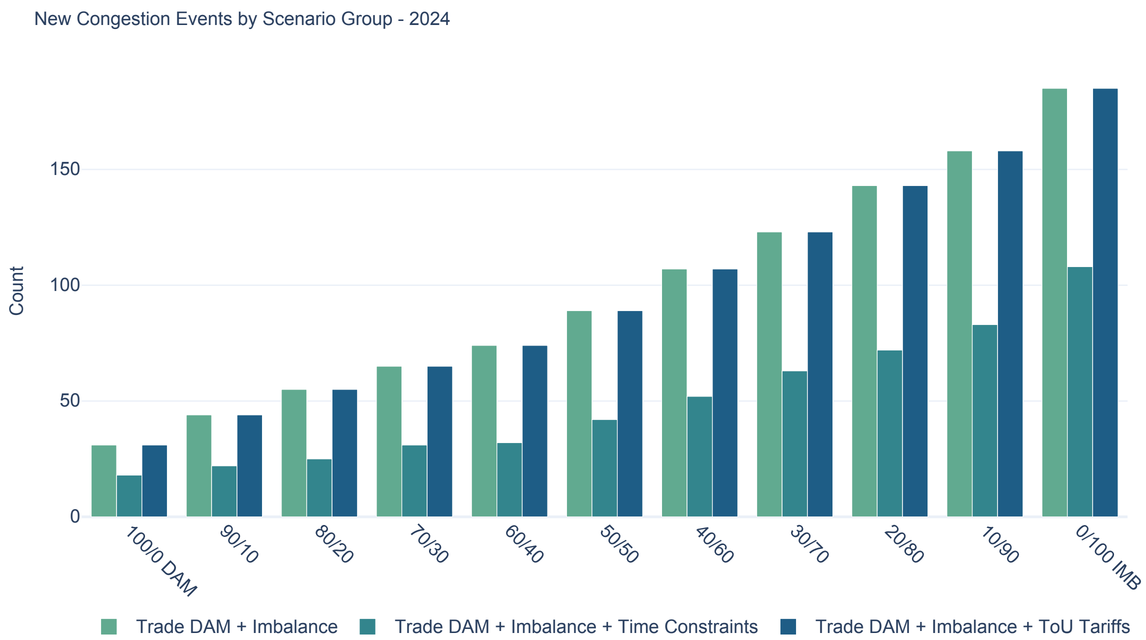


Figure 4.10: Impact of market strategy and congestion-neutral constraints on new congestion events.

Figure 4.11 presents the count of mitigation events, representing periods in which battery discharge relieves grid congestion. As shown in the figure, mitigation is most effective under day-ahead trading. This can be explained by the behavior of the battery, where the battery operation corresponds to the trend of the market. The battery charges during times of low prices and discharges with high prices, therefore supporting the grid. The introduction of time constraints reduces the number of mitigation due to restrictions on discharge during peak hours. ToU tariffs maintain similar mitigation levels to the baseline.

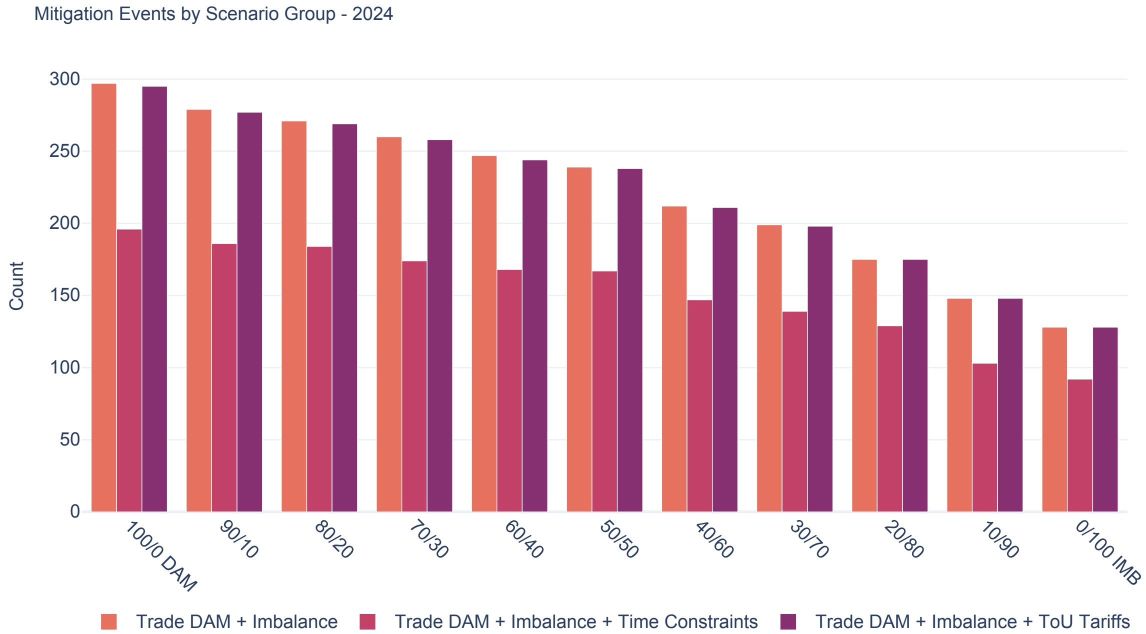


Figure 4.11: Impact of market strategy and congestion-neutral constraints on mitigation of congestion.

Change in grid load over time

Figure 4.12 compares the battery charging and discharge profiles in each strategy. As in the previous sections, if only two scenarios are shown, this represents the day-ahead and imbalance market. The decision was made to visualize these scenarios because those are the most extreme values. The figures visualize the sum of the charging and discharging power per timestep. In the baseline case (green line), charging occurs in two distinct peaks in day-ahead trading: one in the early morning and a more prominent one around midday, reflecting the daily energy prices. When time constraints are applied (red line), a significant portion of charging is curtailed. While this could result in less grid stress during high peak moments, the charging periods shift to periods just before and just after the constrained periods. While this behavior change does not increase the amount of new congestion periods just outside the constrained periods in this case, it could do so for other load profiles at other MSRs.

In contrast, the ToU tariff scenario (dark green line) shows no significant reduction in charging and discharging during the day compared to the baseline. While the ToU tariffs result in minor differences in charging and discharging, the pattern remains almost identical. This implies that while ToU tariffs offer a price-based steering mechanism, they may not be strong enough to prevent charging or discharging during congestion periods if the batteries are controlled by an aggregator. For the day-ahead market, this is because the tariffs already align with existing day-ahead charging behavior. Namely, being lowest at night and around solar noon, precisely when the battery charges. So the ToU tariffs provide no additional economic incentive to alter operation. Moreover, the ineffectiveness of ToU rounding on imbalance pricing is underscored by a mean absolute percentage difference of just 0.1033%, meaning that, on average, the shortage price with ToU rounding deviates from the original by only one-tenth of one percent. This highlights further evidence that, due to the relative high imbalance prices, the tariff has an insignificant impact imbalance prices.

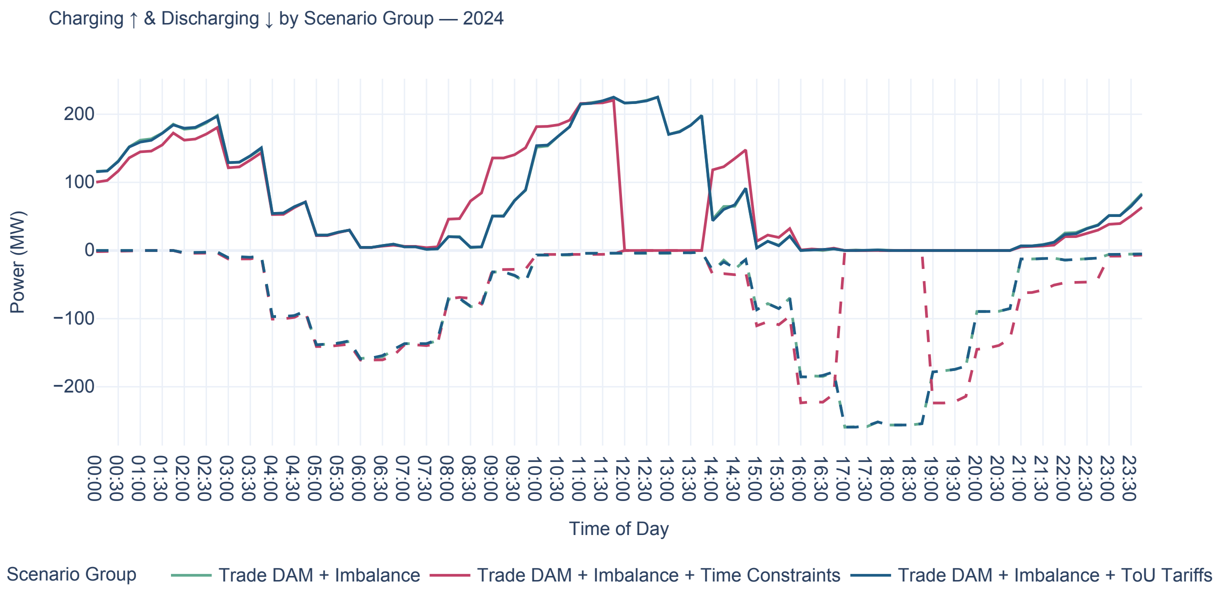


Figure 4.12: Effect of congestion-neutral strategies on day-ahead battery charging and discharging profiles. The dashed line represents discharging behavior of the scenarios.

Figure 4.13 shows how these interventions affect battery behavior in the imbalance market. As noted in earlier sections, the charging and discharging behavior is more distributed throughout the year. Unlike the day-ahead market with predictable daily patterns, the imbalance market lacks consistent timing, with imbalance signals occurring at any moment, as illustrated in the graph. This unpredictable nature makes it more challenging to effectively implement time constraints. While constraints still increase charging and discharging behavior outside the designated windows due to the larger temporal spread, the effect is less pronounced compared to markets with more predictable patterns. The ToU tariff scenario again produces no significant effect on battery behavior, suggesting that the ToU tariffs do not outweigh the high profits on the imbalance market. These differences highlight the larger impact of rule-based enforcement over price-based incentives as strategies for congestion-neutral battery operation. It should be noted that this is the case for optimizing under perfect foresight and from an aggregators perspective.

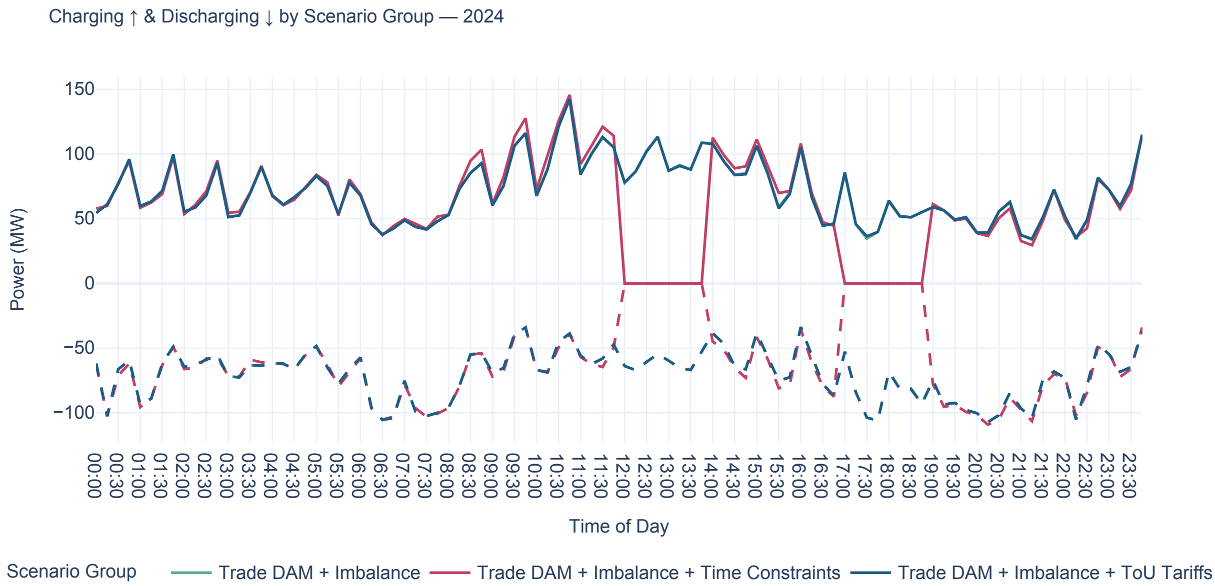


Figure 4.13: Effect of congestion-neutral strategies on imbalance market battery charging and discharging profiles. The dashed line represents discharging behavior of the scenarios.

Effect on peak shaving

Figure 4.14 shows the effect of each strategy on peak shaving. A representative day is displayed to make the graph easier to interpret. This day is representative because it was a weekday in winter and therefore shows regular behavior with a relatively high electricity demand. The baseline and ToU scenarios reduce the net household load during the evening peaks. However, they increase congestion around noon when prices are low. In contrast, time constraints partly prevent discharging during these hours, resulting in a net load profile that closely follows the original demand curve. Although this avoids increasing congestion, it also reduces the business case of the battery. For the day-ahead market, battery profit decreases with 24.9% and for the imbalance market, the profit drops with 22.7%.

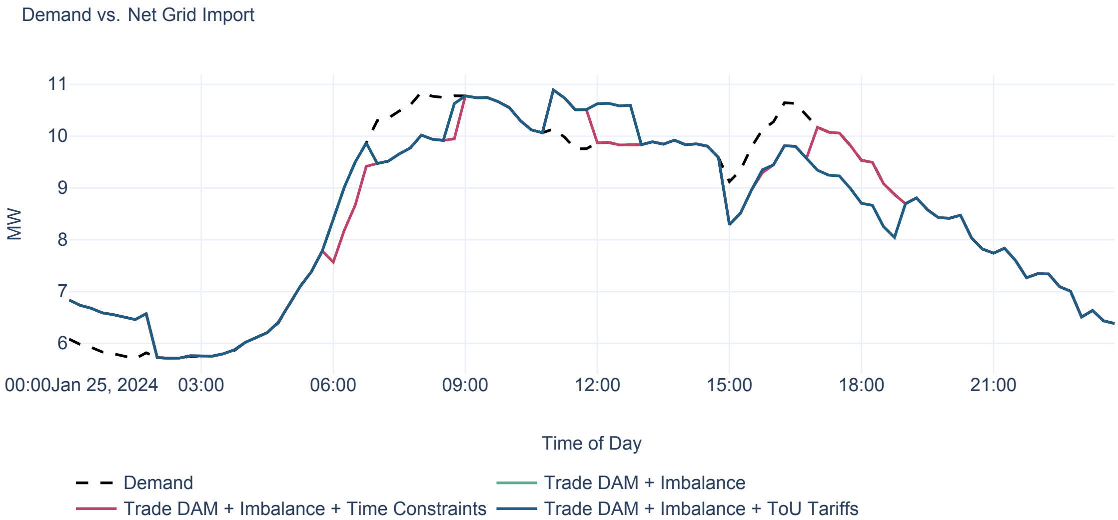


Figure 4.14: Impact of congestion-neutral strategies on peak shaving and net household load for a representative day in January. The dashed line represents the cumulative demand of the households. Every black dashed line in this research can be interpreted as cumulative demand.

As the previous figure shows peak shaving for a representative winter day, Table 4.1 reports the maximum load at the MSR across scenarios. In all scenarios, the maximum load stays constant for all scenarios. However, in imbalance trading, maximum load levels increase, exceeding the base load and indicating the need for additional grid capacity. These findings underscore that imbalance-driven battery control not only increases congestion occurrences but may also require network upgrades.

Group	Scenario	Max Flow to Household (MW)
Base Load	–	11.54
No Congestion–Neutral Implementation	100_0	11.54
Time Constraints	100_0	11.54
TOU Tariffs	100_0	11.54
No Congestion–Neutral Implementation	0_100	**12.10**
Time Constraints	0_100	12.04
TOU Tariffs	0_100	**12.10**

Table 4.1: Maximum flow to household under different scenarios.

Effect on total system costs and profitability of the battery

System costs increase as a result of increased arbitrage potential. The baseline configuration consistently results in the lowest total costs. Time constraints lead to the highest costs, primarily due to lost opportunities during restricted hours. ToU tariffs result in a slight cost increase compared to the baseline, with minimal influence on the grid.

Scenario	100_0 (€)	0_100 (€)
DAM + Imbalance	-95.6k	**-377.7k**
DAM + Imbalance + Time Constraints	-71.8k	-291.7k
DAM + Imbalance + ToU Tariffs	-95.5k	-377.5k

Table 4.2: Total system costs for different scenarios.

4.3. Impact of Value Stacking on Grid Load and Economic Feasibility - 2024

Although R-BESS are often evaluated and used in the context of a single application, such as energy arbitrage, their sustainable business case lies in value stacking. As mentioned in the interview analysis, all stakeholders and actors do not foresee a positive business case for R-BESS with only energy trade. Therefore, the R-BESS should be used for different applications. In this section, the model is extended beyond pure market trading to incorporate self-consumption of solar generation. In addition, the battery should support the system to meet demand, enabling households to reduce imports from the grid. This approach reflects a more future-proof system, where residential batteries are increasingly used not only for market participation, but also to maximize self-generated solar energy.

In terms of stakeholder values, value stacking aligns with the goals of different stakeholders. First, households prefer reduced electricity bills and more independence of the grid to avoid unexpected high bills. Moreover, DSOs are planning to introduce higher net tariffs to shift demand and finance their grid expansion costs. As well, grid operators benefit from reduced peak demand which could potentially be provided by efficient R-BESS usage.

The following subsections assess the impact of value stacking on grid load and how congestion-neutral strategies affect grid impact and economic feasibility. First, adding PV will be addressed. Afterwards, this section will dive into seasonal and time-specific patterns and ultimately into the effect of implementing congestion-neutral strategies.

4.3.1. Adding PV

This section introduces the PV generation in the household energy system of the model. With this addition, the battery no longer relies solely on electricity markets for charging but can also utilize excess solar generation from PV. This enables a value stacking strategy, where the battery serves both as a trading asset and as storage for locally generated solar energy. The following analysis examines how this change affects battery behavior and grid load.

To quantify the impact of PV integration, the key congestion-related metrics were compared across scenarios with and without PV, and under varying ratios of day-ahead and imbalance market participation. The results are summarized in Table 4.3.

Scenario	Already Congested	New Congestion	Charging During Congested	Neutral Charging	Mitigation
DA+IMB 100_0	746	37	44	**10 209**	**298**
DA+IMB + PV 100_0	575	6	9	10 155	260
DA+IMB 50_50	746	65	**218**	9 290	238
DA+IMB + PV 50_50	575	35	145	9 371	198
DA+IMB 0_100	746	**186**	170	9 074	229
DA+IMB + PV 0_100	575	125	151	9 291	161

Table 4.3: Congestion event counts by scenario.

Several differences are the result of the comparison across scenarios. In all cases, the integration of PV results in lower levels of new congestion, fewer charging events during already congested periods, and a decrease in mitigation events. Additionally, the number of events occurring during already congested periods declines in every PV scenario, suggesting that the battery system charges more strategically or makes greater use of self-generated solar energy during high-stress hours. These results mainly derive from the decrease in grid load around noon plus the amount of solar energy that can be stored directly in the battery without charging from the grid.

In addition to congestion metrics, PV integration affects the flow of energy within the household system. Figure 4.15 illustrates the differences in total grid load between the scenarios. The figure shows the sum of total electricity flow from the MSR to the households per timestep in MW.

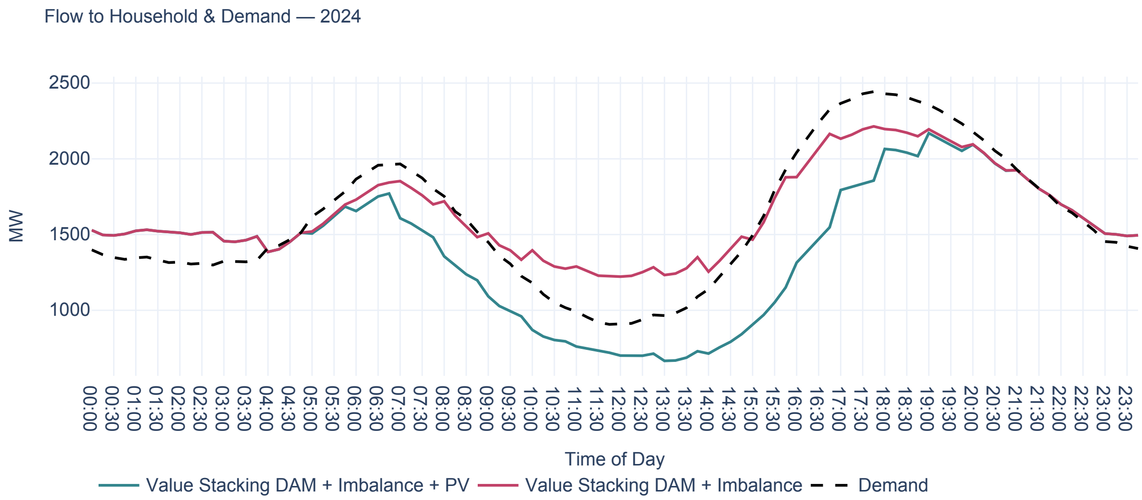


Figure 4.15: The difference in load levels between a network with extra PV or without. The R-BESS in this plot is for 100% used in the day-ahead market.

The figure illustrates how PV integration reshapes household energy flows throughout the day with 100% day-ahead market trading. During midday hours, solar generation is used directly to meet household demand, while surplus energy is stored in the battery. Later in the day, particularly in the evening, when the PV output drops and household consumption increases, the battery is discharged to supply the remaining load. As a result, the household's reliance on grid imports is reduced. For 100% imbalance trading the same pattern, showed in Appendix F.4, results from adding PV. However, due to imbalance trading there are still periods after 19:00 that the total demand of the households and charging the battery exceeds the demand curve and therefore there is no overall decrease in grid impact. This behavior demonstrates that PV integration enhances self-consumption, flattens the household's net load profile, and lowers stress on the grid especially when the trading strategy is focused on the day-ahead market.

4.3.2. Impact of R-BESS on Grid Load

This section explores both seasonal and intra-day patterns in battery operation and its relationship to congestion. All results presented here are derived from the complete 2024 simulation runs across all modelled value stacking scenarios. The scenarios that are actually covered in the plots will be discussed in the corresponding section. These insights first support a general understanding of when congestion is most critical throughout the year. Afterwards, the results of the time-specific congestion patterns will be shown.

Seasonal behavior

As seasonal trends generally follow the same patterns observed in previous sections, namely higher stress during winter and stable operation during summer, the figure is left out of this section and is instead provided in Appendix F.4 for reference.

Intra-day patterns in the day-ahead and imbalance market

This subsection focuses on time-specific behavior, using 15-minute resolution heatmaps to assess when congestion mitigation, congestion-causing charging, or new congestion times occur during the day. Heatmaps are used in this section in comparison with the trade scenario, because the bar plots show similar results. Moreover, the figures cover the complete scenario space representing the difference between using the battery 100% for the day-ahead market and 100% for the imbalance market. For charging during already congested periods, a clear concentration is visible around noon for the day-ahead market and between 16:00 and 18:30 for scenarios including the imbalance market, peaking sharply around 17:15. The frequencies of the charging events during already congested periods are shown in Figure 4.16. This time window overlaps with the well-known residential evening demand peak, when households return home, and with the low energy prices around noon due to high PV energy inflow. An interesting insight is that these congested events during the afternoon and the start of the evening do not occur for day-ahead trading and become significant from the 10% imbalance ratio towards the 100% imbalance ratio. This shows the congestion-neutral behavior of the day-ahead market, where during high demand periods and high price periods the battery discharges and supports the demand serving of households without increasing congestion.

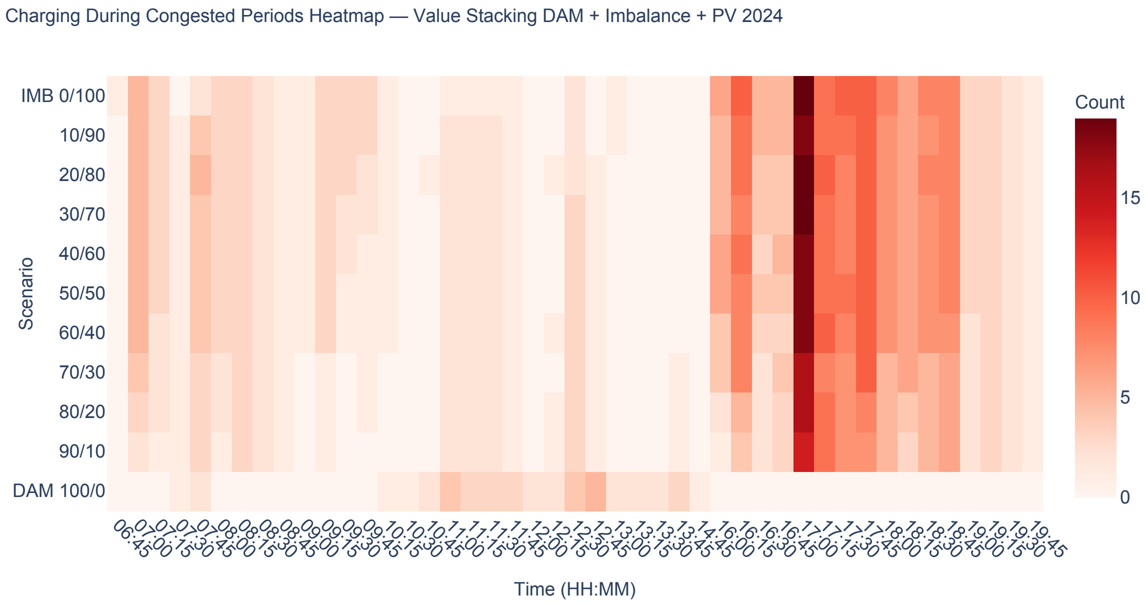


Figure 4.16: Time-specific distribution of charging during already congested periods across different market participation ratios.

Figure 4.17 presents the distribution of new congestion events that arise due to battery charging. These events in the day-ahead market do not occur during peak hours in the evening. This underscores the insight from the previous section that the battery acts congestion-neutral during peak times. Due to the introduction of PV, there are almost zero new congestion periods around noon, while there were more events without PV. For the imbalance market, new congestion periods occurring during peak times in the morning and afternoon. Because balance signals from the TSO are more unpredictable and distributed throughout the day, the battery could charge during high peak and high price events on the day-ahead market, but still gain revenue through the settlement prices of the imbalance market. This timing overlaps with existing congestion windows and periods of low solar generation and high market prices, showing that batteries charge at the worst possible moments for grid stability. The insight supports the concerns from CE Delft and the DSO that imbalance trading could increase grid congestion throughout the day.

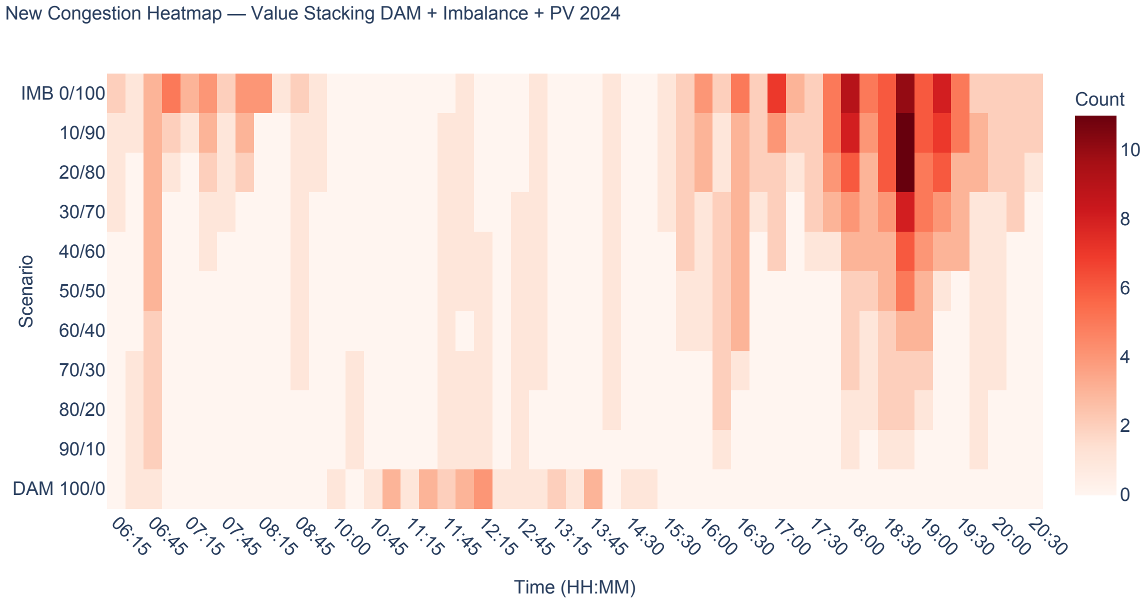


Figure 4.17: Time-specific distribution of new congestion events caused by battery charging across different market participation ratios.

In addition to decreasing grid stability due to battery charging, batteries could also have positive effects on grid stability. Figure 4.18 illustrates the time-specific occurrence of congestion mitigation through battery operation. The mitigation events are significant around the late afternoon, aligning directly with the most congested periods in the Dutch grid. This effect is observed in almost all scenarios, with the highest occurrences in the day-ahead market. This suggests that value-stacked battery operation can substantially support grid stability during peak demand windows, especially when the trading strategy is focused on the day-ahead market. Another observation is a secondary mitigation window that occurs around 06:30 to 08:00, which corresponds to the morning ramp up. Although weaker, this indicates that batteries are discharging during early morning hours to meet household demand, helping to reduce the grid load. These results show the grid-supportive potential of value stacking.

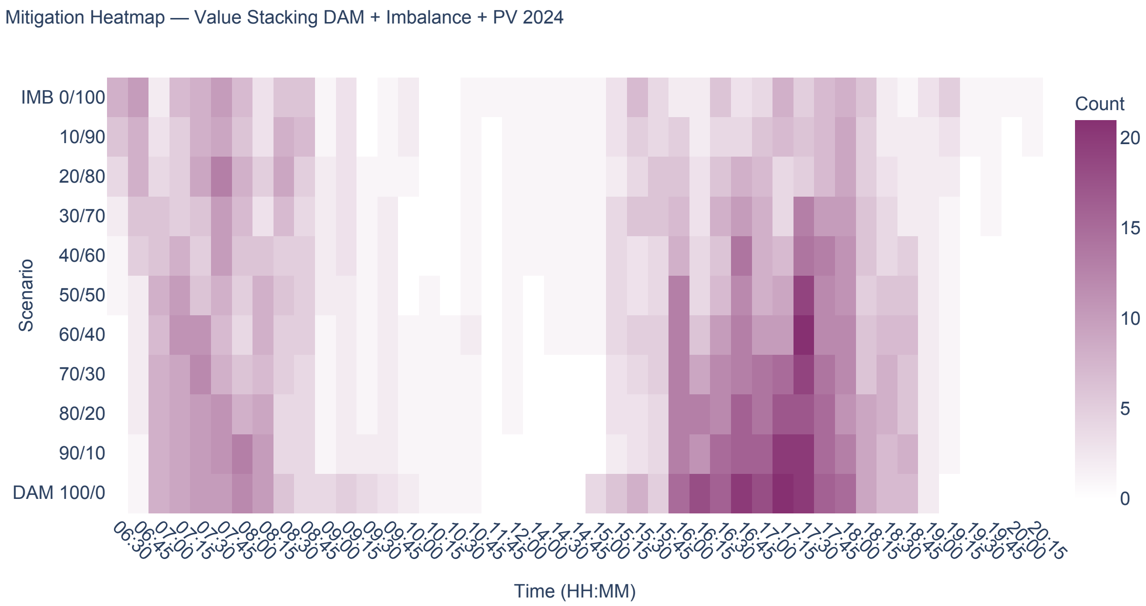


Figure 4.18: Time-specific distribution of congestion mitigation events through battery discharging across different market participation ratios.

4.3.3. The Effect of Applying Time Constraints or ToU Tariffs on Grid Load

Although value stacking already offers a promising combination of market participation and PV self-consumption, uncoordinated battery behavior can still lead to charging or discharging at moments of grid congestion or create new congested periods. To address this, two congestion-neutral strategies are implemented in the model: time constraints and ToU tariffs. The time constraint strategy restricts battery operation between 12:00 and 14:00 and between 17:00 and 19:00. The ToU tariff strategy, on the other hand, applies a dynamic pricing structure that increases net costs during peak grid stress, thereby discouraging battery charging at those times. The following subsection analyzes how these strategies affect battery charging and discharging behavior.

Effect on congestion events

Implementing congestion-neutral strategies can have an impact on the amount of congested events and mitigated events. Therefore, both strategies are modelled across varying day-ahead and imbalance market ratios (from 100/0 to 0/100). So in total three scenario groups: baseline value stacking, value stacking with time constraints, and value stacking with ToU tariffs. All relevant graphs for this section have been moved to Appendix F.5 to improve readability in the main text, as the results are similar to the trade scenarios. The first metric illustrates charging during congested periods. The trend that this type of charging increases as the imbalance market share grows is clearly visible. Among the strategies, time constraints are the most effective in reducing this behavior. In full day-ahead operation, such events are relatively limited, with 9 events without constraints and 2 events with time constraints. However, under high imbalance trading, the number of conflicting charging events increases significantly with 150 and 65 occurrences, respectively. ToU tariffs, on the contrary, show no significant impact, with 150 without and 151 counts with ToU tariffs. This demonstrates that price-based signals alone are insufficient to reduce the occurrence of charging during congested periods under the circumstances of perfect forecast and trading operated by an aggregator.

New congestion events, follow a similarly clear upward trend as the system shifts from day-ahead to imbalance operation. While all strategies experience increases under higher imbalance shares, time constraints help to limit the number of new congestion events effectively. In the day-ahead market, the events decrease from 6 to 3 and in the imbalance market from 125 to 73.

Moreover, the battery behavior also mitigates congestion. These events in the day-ahead market typically occur by discharging during system peak hours. The results indicate that mitigation is most significant in day-ahead trading scenarios, with lower effectiveness under imbalance-focused configurations. However, when implementing time constraints, mitigation events decrease from 260 to 163 and 161 to 121 for the day-ahead market and imbalance market respectively. This illustrates the negative effect of restricting the battery. Overall, the outcomes confirm that day-ahead trading offers the most grid-supportive behavior and the lowest incidence of both new congestion and charging during already congested periods.

Change in grid load over time

Under day-ahead trading, the baseline and ToU scenarios display similar patterns, with two charging peaks and strong evening discharging. Time constraints shift charging activity away from the restricted periods, concentrating it just before and after, which may increase risks depending on the load levels of the MSR.

Under imbalance trading, charging and discharging are more dispersed. Time constraints still limit activity during peak hours, but the effect is smaller due to the larger distribution of charging. Again, ToU tariffs have little effect on altering dispatch behavior.

Effect on peak shaving

Another important metric to assess the impact of congestion-neutral strategies on grid load is the overall peak shaving due to battery behavior. Figure 4.19 illustrates the impact of battery operation on the net household load throughout the day, summed per timestep for one year. The dashed black line represents the original household demand without battery intervention, serving as a reference for assessing load shaving effectiveness.

The largest differences between the scenarios are observed during the evening. While both the baseline and ToU scenarios continue to deliver substantial load shaving, the time constrained scenario allows no battery discharging. As a result, the red line follows the original demand curve.

These results show that time constraints effectively avoid battery operation during congested periods but at the cost of reduced load shaving when it matters most. The ToU tariff scenario, on the other hand, behaves nearly identically to the baseline, suggesting that price signals alone were insufficient to shift battery activity during peak times.

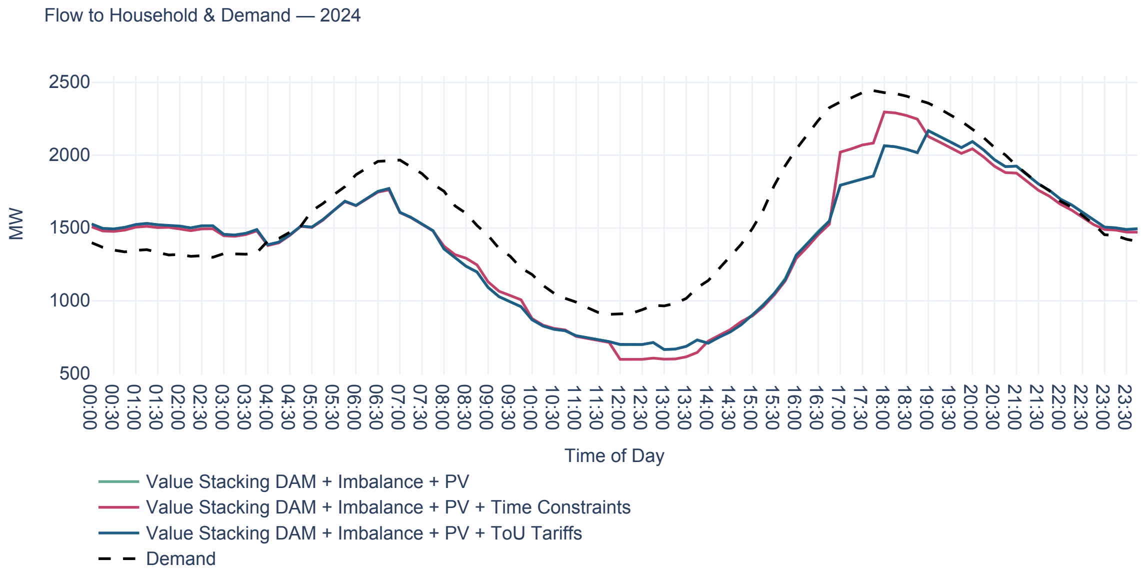


Figure 4.19: Impact of congestion-neutral strategies on household net load profile across the day.

However, the last figure shows a more general result of the impact of battery behavior on grid load. To ensure grid stability, the DSO still needs to account for maximum capacity. Therefore, the maximum load throughout the year was retrieved from the model to show which capacity is needed for this particular MSR. In Table 4.4, it is shown that for day-ahead market trading a lower capacity is needed, which can save the DSO an investment in grid expansion. Nevertheless, as 100% imbalance trading is still possible, the maximum grid load exceeds the base load. The imbalance flow is somehow similar with higher peaks in the early morning and a higher peak for the scenarios without time constraints in the evening. This plot is illustrated in Appendix F.4.

In conclusion, where imbalance trading results in more congestion periods and fewer mitigation periods, it also increases the maximum capacity that is needed for the MSR.

Group	Scenario	Max Flow to Household (MW)
Base Load	–	11.54
No Congestion–Neutral Implementation	100_0	10.81
Time Constraints	100_0	11.27
TOU Tariffs	100_0	10.81
No Congestion–Neutral Implementation	0_100	**12.10**
Time Constraints	0_100	12.04
Value Stacking DAM + Imbalance + PV	0_100	**12.10**

Table 4.4: Maximum flow to household under different scenarios, including value stacking.

Effect on total system costs and profitability of the battery

In addition to the effect of battery behavior on grid impact, the effect on economic feasibility also has to be investigated. The total costs of the system, for different trade ratios and strategy scenarios, are shown in Figure 4.20.

System costs decrease steadily as the imbalance market share increases, reflecting the higher arbitrage potential in that market. The baseline scenario (without constraints) consistently achieves the lowest costs, while the time constraint strategy results in the highest, due to its strict operational limits during congested periods, which prevents the battery from discharging during high price moments and charging during low price moments. Overall, implementing time-constraints result in a 0.9% increase in overall system costs for the day-ahead market and 3.47% for the imbalance market. The ToU tariff scenario performs close to the baseline, with only a minor cost increase.

These results highlight a clear trade-off: congestion-neutral strategies reduce grid impact but come at an economic cost. Where time constraints are most effective for de-stressing grid load but limit profitability, ToU tariffs seem to have no significant impact on grid load and come with a limited increase in total system costs.

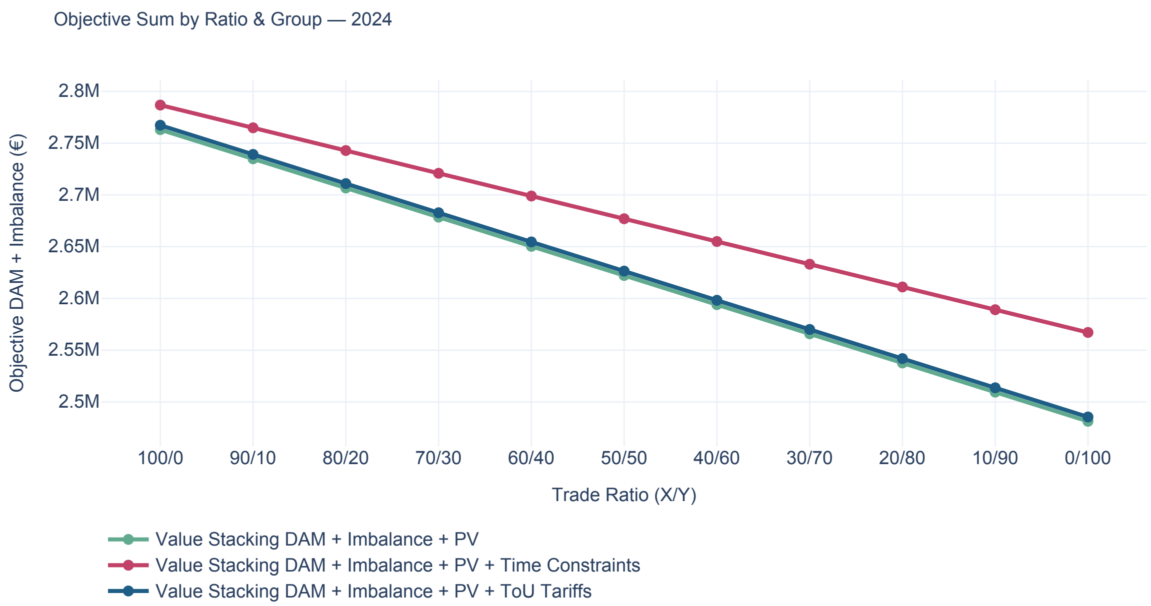


Figure 4.20: Total system costs under different market participation ratios and congestion-neutral strategies.

Scenario	100_0 (€)	0_100 (€)
DAM + Imbalance + PV	2763k	**2481k**
DAM + Imbalance + PV + Time Constraints	2787k	2567k
DAM + Imbalance + PV + ToU Tariffs	2767k	2485k

Table 4.5: Total system costs for different scenarios.

4.4. Impact of Value Stacking on Grid Load and Economic Feasibility - 2030

To evaluate the long-term performance of value stacking strategies, the simulation framework has been extended to represent the system conditions projected for the year 2030. Liander made a forecast of the load levels in 2030 based on the 2024 load levels. The 2024 data is scaled to 2030 by taking into account increasing residential electricity demand and a greater renewable energy generation. Until 2032, Liander does not expect to finish the grid expansion, and therefore, the same capacity on the MSR is used. The increase in the number of batteries and solar panels is based on forecasts from TenneT and Netbeheer Nederland. This is explained more in detail in Section 3.3.3. The purpose of this section is to examine the impact of R-BESS on the load levels and the economic feasibility of the system. As value stacking is the only sustainable business model in the future, according to stakeholders, this section will focus solely on value stacking scenarios.

4.4.1. Impact of R-BESS on Grid Load

This section explores both seasonal and intra-day patterns in battery operation and its relationship to congestion. All results presented here are derived from the complete 2030 simulation runs across all modelled value stacking scenarios.

Seasonal behavior

To better understand when congestion becomes critical for this specific MSR, seasonal patterns are analyzed. Figure 4.21 presents the monthly distribution of congestion-related events in 2030, including the frequency of pre-existing congestion.

As in the 2024 scenario, a seasonal trend is visible. Congestion is most severe in the winter months, when both existing and new congestion events peak. These months also show charging during congested periods, indicating an increased risk of grid failure. However, the intensity of winter congestion in 2030 is significantly higher, suggesting that rising electrification and limited grid expansion further increases grid stress. Moreover, the congestion events spread out towards the autumn and spring months, which shows that congestion will be an issue throughout the year in the future until the grid expansion is finished.

In contrast, the summer period still shows a near absence of new and already congested periods for day-ahead market trading. Battery operations during these months are predominantly neutral, supported by high PV output and lower electricity demand. However, for the imbalance market congestion events start to occuring even in summer. The plot (Appendix F.5) illustrates that if the 2030 imbalance market is not fully saturated by BESS, summer-specific congestion events will result from the trading behavior of the R-BESS. This highlights the importance of expanding the grid capacity and restricting battery behavior.

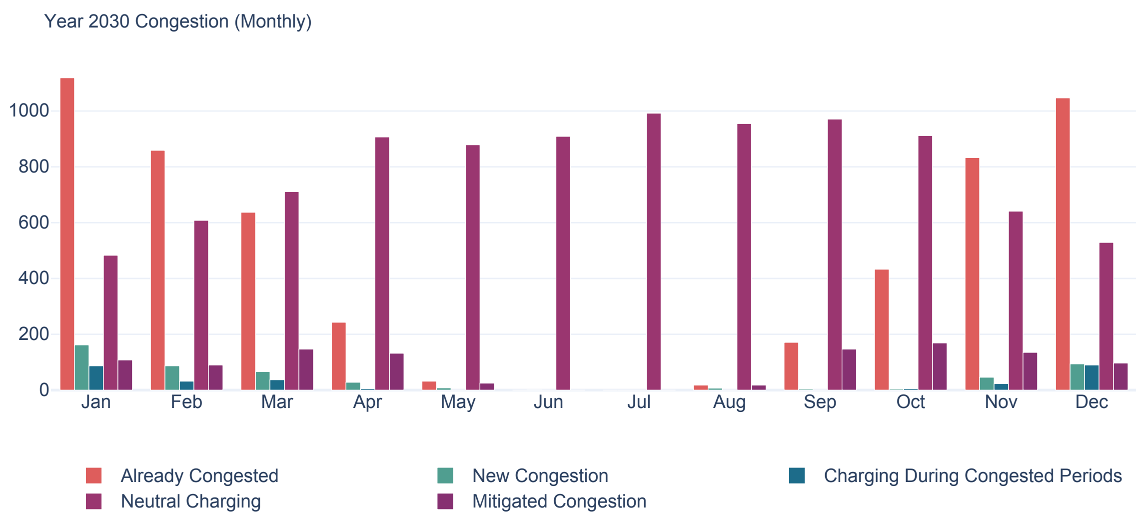


Figure 4.21: Seasonal behavior and grid impact of the R-BESS.

Intra-day patterns in the day-ahead market

After identifying the seasonal pattern of congestion, a more in-depth understanding of specific time patterns supports understanding of congestion periods throughout the day.

Charging activity (Appendix F.3, Figure F.8) shows a clear trend, with peaks during early morning hours (05:00-07:00) and around noon. Most charging occurs under neutral conditions. Despite this, there are several periods in which the battery charges during already congested periods. This behavior underscores the largely congestion-neutral behavior of the battery, while there are several periods in which charging the battery increases grid stress.

Figure 4.22 further illustrates the impact of battery behavior by plotting existing congestion, new congestion events, and mitigation effects throughout the day. Congestion is most prominent during the morning and evening peaks. Crucially, these same periods indicate the strongest mitigation in which battery discharge actively reduces grid stress. In terms of new congestion periods, during the night, battery charging results in several new congested periods. This insight shows that, while DSOs describe 12:00-14:00 and 17:00 and 19:00 as crucial periods, even future night-time periods can become important periods to monitor. However, with the expansion of the grid, these congestion periods are expected to be solved.

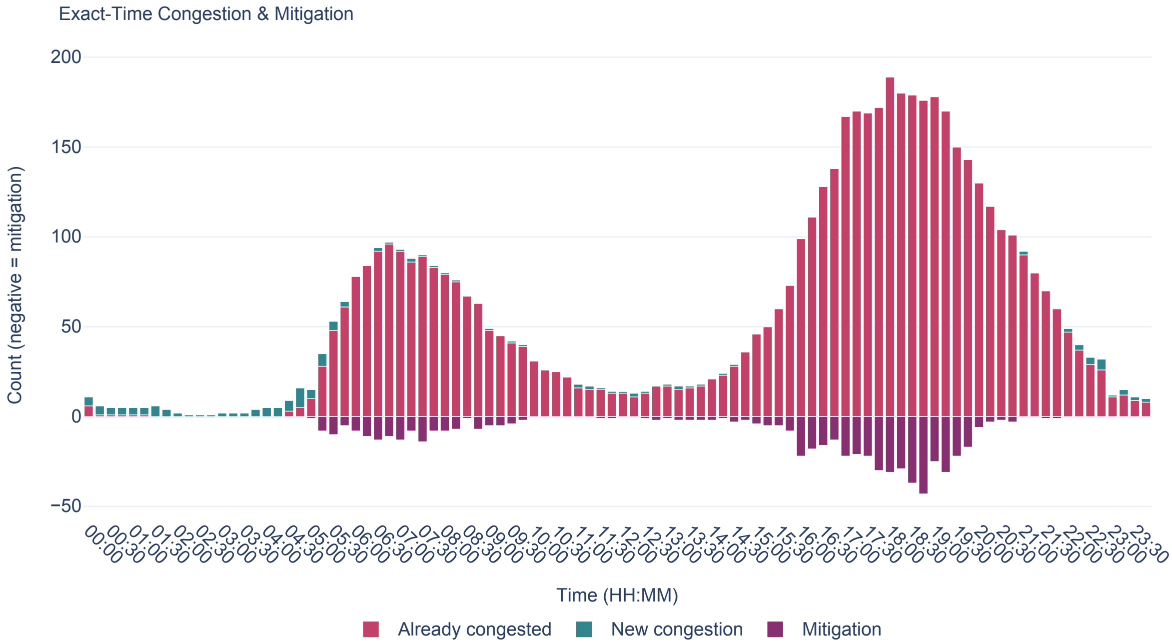


Figure 4.22: Distribution of existing congestion, new congestion events, and mitigation effects across the day for the day-ahead market.

Intra-day patterns in the imbalance market

For the imbalance market, charging activity (Appendix F.3, Figure F.9) shows a broad distribution throughout the day, with elevated activity between 10:00 and 17:00 and again after 21:00. Unlike the day-ahead case, charging occurs during more periods throughout the day and lacks clearly defined peaks. Importantly, a considerable share of this charging occurs during already congested periods, particularly in the late afternoon and early evening. This pattern reflects the imbalance trading market, where real-time price signals encourage responsiveness, often without regard to local grid constraints. Although neutral charging still dominates, the frequency of charging during congested periods is markedly higher than in the day-ahead scenario.

Figure 4.23 provides further insight into the consequences of this behavior. Evening hours are the most beneficial for congestion in terms of reducing congestion. During these periods, mitigation effects are present but weaker than in the day-ahead scenario.

New congestion events are more evenly distributed across the day than in the day-ahead case, with noticeable counts in the afternoon and early night hours. These patterns highlight the increased operational risk of real-time imbalance optimization. It namely results in less constant and less coordinated battery behavior, which is hard for both aggregators to exploit the market and for DSOs to regulate the market. For the 2030 scenarios, heatmaps are plotted to show the ratio between 100/0 day-ahead capacity towards 0/100 imbalance capacity. A complete analysis can be found in Appendix F.6.

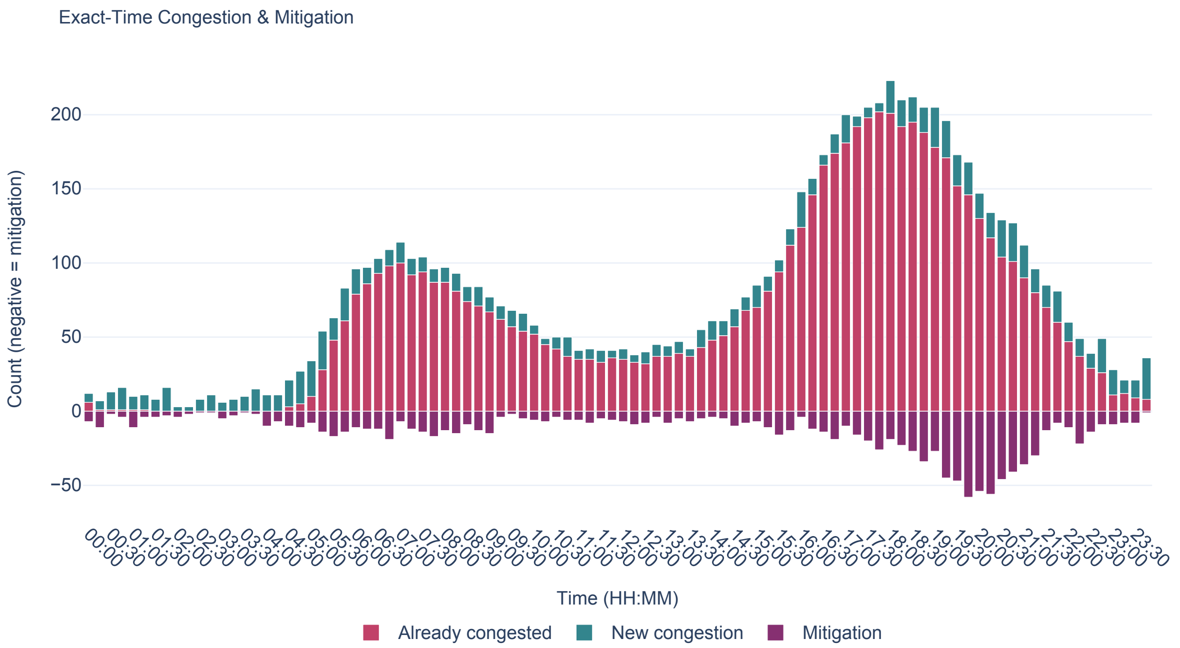


Figure 4.23: Distribution of existing congestion, new congestion events, and mitigation effects across the day for the imbalance market.

4.4.2. The Effect of Applying Time Constraints or ToU Tariffs on Grid Load

The introduction of congestion-neutral strategies does not fundamentally alter the behavioral patterns in comparison with 2024. Charging and discharging the battery still shifts outside of the constrained periods for the time constraints scenario. Introducing ToU tariffs will not significantly affect battery behavior. However, due to the increased installed battery power and capacity in the 2030 case, the absolute scale of energy flows is higher. This underscores the risks of the non-restricted battery behavior. As battery deployment scales further in 2030, electricity demand increases and grid expansion stays behind, regulations are needed to restrict or steer the battery behavior. For the 2030 scenario, time-based operating constraints and the ToU tariff will be analyzed.

Effect on congestion events

The results for 2030 highlight how congestion-neutral strategies influence the relationship between battery behavior and grid congestion across varying configurations. Charging during congested periods (Appendix F.5.1) shows the same behavior as the scenario of 2024. Under day-ahead dominance, such charging remains limited. However, as the imbalance share increases, the amount of charges during congested periods increases for all scenarios. Time constraints again prove to be an effective way to drop the count of congested charges.

Compared to the 2024 scenario, new congestion events (Figure 4.24) first drop as the system changes from day-to-day to imbalance-dominant operation and ultimately increases. This drop is mainly the result of the large amount of new congestion periods during the night which decrease as the ratio of day-ahead decreases. Among the strategies, time constraints consistently yield the lowest number of new congestion events, while ToU tariffs offer only minimal improvement.

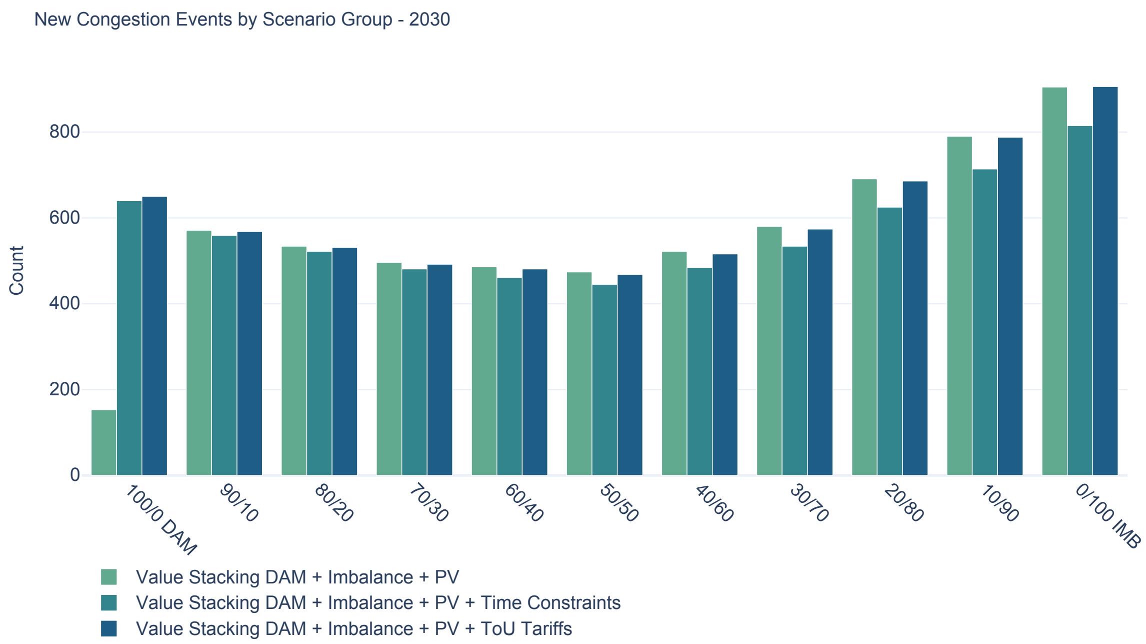


Figure 4.24: New congestion events across different market participation ratios and congestion-neutral strategies.

Mitigation events, on the contrary, remain relatively stable across all trade ratios and strategies. As the result is a stable count of mitigation events, the plot can be found in Appendix F.5.1. Notably, both the baseline and ToU tariff scenarios achieve similar mitigation levels, while time-constrained operation decreases the amount. Nonetheless, with this insight, the higher value of day-ahead over imbalance trading in terms of mitigating congestion is diminished.

Change in grid load over time

The introduction of congestion-neutral strategies does not fundamentally alter the behavioral patterns in comparison with 2024. The battery is still charged and discharged outside the constrained periods for the time constraints scenario. Introducing ToU tariffs will not significantly affect battery behavior. However, due to the increased installed battery power and capacity in the 2030 case, the absolute scale of energy flows is higher. This underscores the risks of changing battery operation with time constraints. As there is a higher load shift due to charging and discharging and no grid expansion, the grid could become more congested. As behavioral trends closely mirror those analyzed in 2024, detailed results are included in Appendix F.7 for reference.

Effect on peak shaving

With more congested periods in 2030 and higher batteries capacity, the load shift that could possibly be created by R-BESS is crucial to reduce the costs for DSOs and thereby potentially decrease the energy bill for households. All strategies significantly reduce peak load relative to the unshaped demand curve, particularly during the evening peak between 17:00 and 21:00. The baseline and ToU tariff scenarios achieve the largest overall load shaving.

In contrast, the time-constrained strategy results in a less effective peak reduction. The disallowance of discharging during critical congestion hours prevents the battery from discharging while the grid is most stressed. As a result, net load remains high during the peak window, closely following the original demand curve.

The general shaping of the morning load is shown in all scenarios during peak times, and the differences in midday are marginal, driven largely by the PV output rather than the different scenarios. The main differences occurs in the evening, where total load for the scenarios without time constraints is significantly lower.

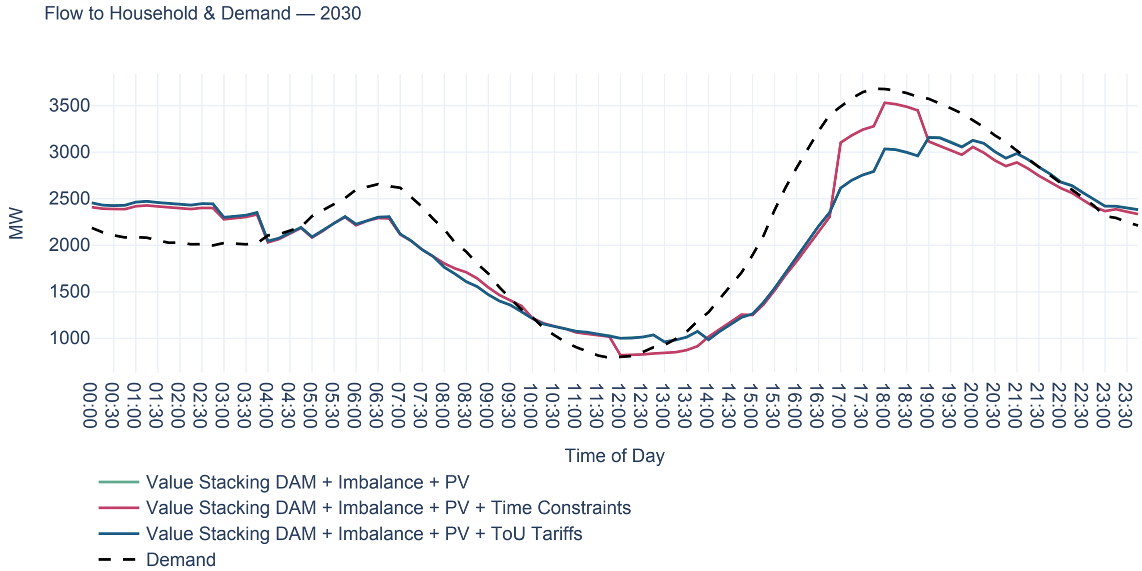


Figure 4.25: The difference in load levels between a network with or without congestion-neutral strategies.

Although peak shaving appears significant in the ToU scenario, this effect is observed primarily in day-ahead market configurations. Moreover, the DSO still needs to account for the maximum capacity across all possible scenarios. Table 4.6 presents the maximum load per scenario, revealing that effective peak reduction is achieved under day-ahead market conditions. In contrast, scenarios dominated by imbalance market participation exhibit higher peak loads, indicating that grid capacity would need to be expanded to cover for the battery behavior in these cases. These findings suggest that in addition to an increase in congestion events, an imbalance-driven operation may need expansion to the distribution network.

Group	Scenario	Max Flow to Household (MW)
Base Load	–	17.02
No Congestion–Neutral Implementation	100_0	16.18
Time Constraints	100_0	16.94
TOU Tariffs	100_0	16.18
No Congestion–Neutral Implementation	0_100	**18.48**
Time Constraints	0_100	17.78
Value Stacking DAM + Imbalance + PV	0_100	**18.48**

Table 4.6: Maximum flow to household under different scenarios.

Effect on total system costs and profitability of the battery

Total system costs in 2030 follow the same trend observed in the 2024 case: costs decrease as the imbalance market share increases, reflecting the higher arbitrage potential in real-time operation. Among the strategies, the baseline configuration consistently yields the lowest costs, while time-constrained operation results in the highest costs due to restricted flexibility during profitable hours. In comparison with the baseline, implementing time constraints result in a 1.3% rise of total system costs for the day-ahead market and 5.09% for the imbalance market. ToU tariffs offer a middle ground, slightly increasing costs relative to the baseline.

However, overall cost levels in 2030 are notably higher across all strategies and trade ratios compared to 2024. This reflects the increased system demand, battery capacity, and market activity under future grid conditions.

As the underlying patterns remain consistent with earlier findings, the detailed breakdown of costs by scenario is included in Appendix F.8.

Scenario	100_0 (€)	0_100 (€)
DAM + Imbalance + PV	4105k	**3517k**
DAM + Imbalance + PV + Time Constraints	4157k	3696k
DAM + Imbalance + PV + ToU Tariffs	4112k	3523k

Table 4.7: Total system costs for different scenarios.

4.5. Sensitivity Analysis

To explore how key modelling assumptions influence grid impact, a sensitivity analysis was performed on PV penetration and battery capacity for the 2024 scenarios. The results are presented in the corresponding sensitivity plots. Both analyses consider the ratio of new plus charging during already congested periods versus the number of mitigation events, to illustrate the trade-off between grid stress and grid support under different parameter levels.

PV capacity

The PV sensitivity analysis (Figure 4.26) reveals a non-linear relationship between PV capacity and grid impact. The size of the bubble represents the system costs, with a larger bubble visualizing higher costs. From 200% to 75% PV capacity, there is a clear increase of mitigation occurrences, while the number of new charging during already congested periods is relatively stable. The overlap of the bubbles reveals that despite substantial increases in costs, the corresponding shifts in battery□related congestion metrics remain limited. In other words, even as the system becomes more expensive, we do not observe proportionally greater improvements in either new congestion avoidance or mitigation events. Please note that these total system costs reflect the net expense of buying all household electricity minus battery profit. Moreover, they do not include the capital costs of the batteries or solar installations.

From 75% to 0% PV capacity, there is a clear increase in the ratio of new plus charging during already congested periods relative to mitigation. In this range, fewer PV generation drives more dependency from the grid and thus midday charging, which in turn contributes to grid congestion. The previous insights suggest a threshold effect: once PV penetration reaches a certain level, further increases no longer significantly worsen congestion, but instead reduce the system's flexibility to mitigate peak demand. In more detail, mitigation periods decrease during the windows 09:00-10:00 and 15:00-17:00, while the new plus already congested periods stay stable. This behavior is consistent across both day-ahead market scenarios, with and without time constraints. In the imbalance market scenarios, the relationship appears more linear, without a clear threshold, reflecting the more continuous and reactive nature of imbalance-based dispatch.

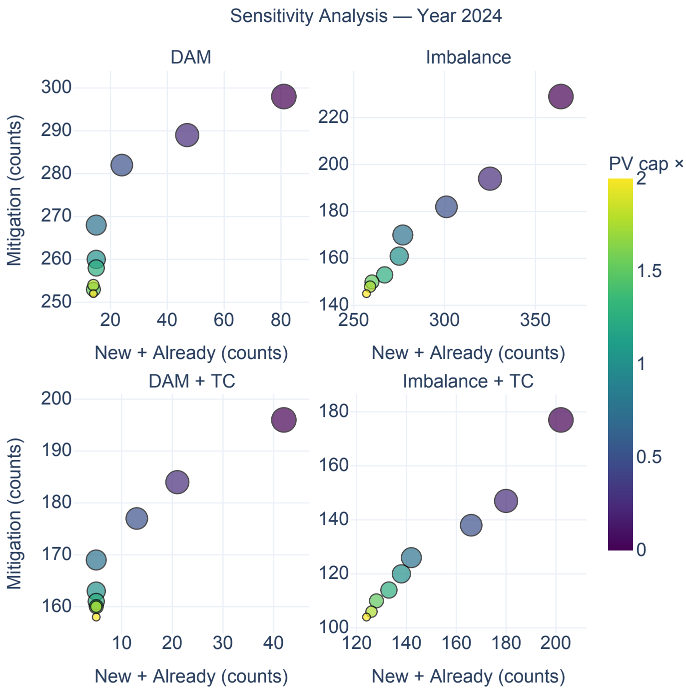


Figure 4.26: Impact of PV capacity scaling on the ratio of new congestion and charging during already congested periods to mitigation events. The bubble size represents the total system costs, with a larger bubble visualizing higher costs.

Battery adoption rate

The battery sensitivity analysis (Figure 4.27) reveals important implications for aggregator strategies. Up to approximately 100% battery adoption rate, adding batteries leads to an increase in mitigation events, as the batteries effectively discharge during peak periods to support the grid. However, beyond this point (from 125% to 200%), a higher battery adoption rate results in a marked increase in new charging during already congested periods, with only limited additional mitigation benefits. This effect occurs, because the discharge events that provide real mitigation are already saturated, so a higher adoption rate only shifts the bottleneck to the charging side. Any additional charging capacity charges more at times that were previously unconstrained, the late evening, overnight and around noon. As that charging volume grows large enough, those windows themselves become congested.

This indicates that for an aggregator operating within this particular MSR, operating batteries beyond a certain threshold may unintentionally contribute to greater grid congestion. This effect is observed in both day-ahead market scenarios, with and without time constraints. In the imbalance market scenarios, the relationship between battery adoption rate and grid impact remains more linear: as battery adoption rate increases, both congestion and mitigation increase steadily, again reflecting the more dynamic nature of imbalance-driven dispatch.

In this of system costs, the bubbles show no overlap, indicating that every scenario produces a unique pair of new plus charging during already congested counts and mitigation events. In practical terms, this separation highlights that incremental changes in battery adoption result in shifts in both congestion occurrence and relief. So, if you increase the adoption rate, and thereby increase battery profitability, there is no convergence on one particular outcome.

Figure 4.27: Impact of the battery adoption rate scaling on mitigation and new congestion plus charging during already congested events. The bubble size represents the total system costs, with a larger bubble visualizing higher costs.

Energy tax

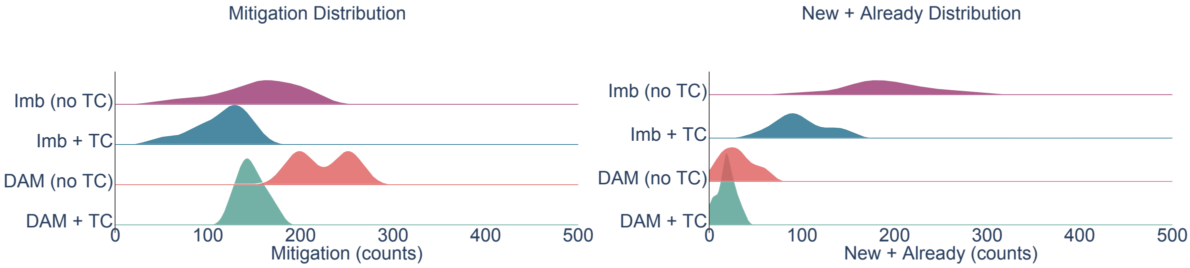
The energy tax sensitivity analysis did not reveal a significant impact on battery behavior in the tested range. Varying the energy tax from 0% to 200% did not result in noticeable shifts in charging or discharging patterns. The new congested periods, charging during congested periods, and mitigation periods had the same values across all scenarios (Appendix F.9). This suggests that under the current market structure, energy tax levels do not strongly influence aggregator-driven battery operation. One might hypothesize that higher energy taxes would stimulate behind-the-meter consumption; however, because the model treats the aggregated households as a single household, self-consumption is already maximized. Furthermore, under perfect foresight, additional tax increases do not influence the battery's dispatch decisions. The results indicate that arbitrage opportunities in the day-ahead and imbalance markets remain the dominant drivers of battery behavior, outweighing the effects of energy tax variation.

Nevertheless, it is possible to comment on total system costs under doubled energy taxes: across the different scenarios, total system costs increase by roughly 0.1%. While this change may seem small in percentage terms, it could ultimately undermine the financial viability of the battery business case. As battery capital and installation costs are not included in this analysis, this insight is provided to alert that the observed increase in system costs may understate the true economic impact.

4.6. Robustness Analysis

The probability density distributions from the robustness analysis illustrate how the key grid impact metrics, mitigation, and new plus charging during already congested periods respond to variations in weather conditions, electricity prices, and load levels in the 2024 scenarios. Narrower distributions indicate more consistent outcomes across the uncertainty space, while broader distributions reflect greater sensitivity. So, with a narrow distribution, the results of the MSR Monnickendam are more generalizable to other MSRs and other weather years. In addition, the position of the peak provides an indication of the most frequent outcome for each metric. In the analysis, R-BESS power and capacity are fixed for each MSR.

To start the robustness analysis, the performance of the model is first tested for ten different weather conditions and electricity prices. The out-of-sample conditions range from 2015-2023 and include the base scenario of 2024. In total, there are 10 different test scenarios. The decision was made not to combine different weather years with other years of electricity prices, as there is a high interdependency between these two variables. The results can be found in Figure 4.28. As shown, particularly the day-ahead market with time constraints shows robust behavior in comparison with the other scenarios. This means that this scenario is more resistant to other weather and price conditions, also showing a peak for the most frequent scenario for both mitigation and new congestion and charging during already congested periods. The other scenarios show a larger distribution and indicate that the outcomes are less consistent with other parameter values.

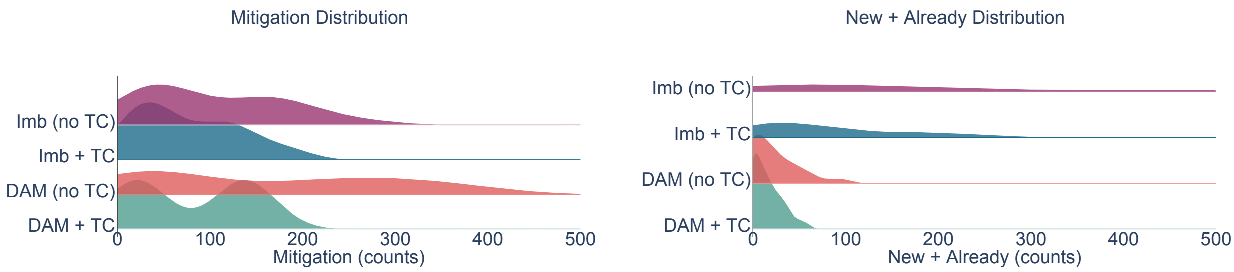


(a) Mitigation events across all scenarios. **(b)** New plus charging during already congested events.

Figure 4.28: Robustness of battery operation under varying weather years and electricity price conditions (2015–2024).

After initially testing robustness across weather and electricity price uncertainty in ten scenarios, we introduced three distinct load levels of MSRs other than Monnickendam, expanding the test set to forty scenarios. The result of this analysis can be found in Figure 4.29. For the imbalance market and the day-ahead market with time constraints, the mitigation event distributions develop two clear concentration zones instead of peaking at a single value, while the imbalance scheme without time constraints shows a more uniformly spread curve with long tails. The day-ahead market without time constraints also broadens its range compared to when only weather and price variations were considered. The appearance of these multiple peaks and the overall widening of the distributions is a sign of weak system robustness and shows that results from one MSR cannot be reliably generalized across different stations. Generalizability means that outcomes from one MSR, for example the number of mitigation events in the day-ahead market when testing time constraints, cannot be directly applied to other MSRs because their characteristics differ, resulting in different metrics.

In contrast, in the new plus charging during already congested periods distribution, day-ahead configurations show robustness, with congestion outcomes concentrated at low values. The results are also more centered towards one most frequent outcome. Imbalance configurations show broader and flatter distributions, highlighting their greater sensitivity to variability and a higher risk of congestion under changing system conditions.



(a) Mitigation events across all scenarios. **(b)** New plus charging during already congested events.

Figure 4.29: Robustness of battery operation under varying weather years , electricity price conditions and load levels (2015–2024).

To expand the robustness analysis, the metrics of day-ahead versus imbalance strategies were examined in the context of substation stress levels (Table 4.8). Schaep (13615 already-congested intervals) and

Monnickendam (5683) represent high-stress MSRs operating close to their capacity limits, while Zaandijk (1312) and Kwadijk (246) are low-stress with substantial spare capacity. Table 4.8 shows that low-stress MSRs have a higher relative mitigation potential, which comes at the cost of a higher relative number of new congested periods. In high-stress MSRs, mitigation potential is constrained: day-ahead dispatch relieves only about 40 percent of congestion in Monnickendam and 22 percent in Schaep, and imbalance trading adds just 27 percent and 12 percent of relief respectively. By contrast, low-stress MSRs clear approximately 38 percent in the day-ahead market and 87 percent in the imbalance market at Kwadijk, and 41 percent and 45 percent at Zaandijk, indicating that R-BESS with the capacity used in de model can be more effective in low stress MSRs. It could also suggest that a higher adoption rate or R-BESS may be necessary to achieve similar benefits station with a high load levels in comparison with their maximum capacity. Linking this hypothesis to the sensitivity analysis (Figure 4.27) confirms that this holds true in both markets. A positive correlation appears between adoption rate and the frequency of mitigation events at high-stress MSRs such as Monnickendam. The steep slope in the imbalance market suggests this trend extends beyond 200%, unlike in the day-ahead market. Overall, increasing R-BESS adoption consistently raises the mitigation percentage for high-stress MSRs across both markets; however, in the day-ahead market this comes at the expense of a lower ratio of mitigation events to the sum of new congested events plus charging during congested periods.

New congestion rates show the same patterns. For the day-ahead market for all scenarios the relative amount of new congested periods is similar. However, high-stress stations experience new congestion in only 15 percent of intervals at Monnickendam and 8 percent at Schaep, whereas low-stress sites experience new congestion in roughly 30 percent of intervals at both Kwadijk and Zaandijk. This could be explained by the already highly congested state of the high-stress MSRs, where there is less potential for additional congested periods. These findings highlight that with the current system conditions, high-stress MSRs show a higher congestion-neutral behavior and low-stress MSRs needs stricter constraints to act congestion-neutral, which will come at the cost of mitigation periods.

Scenario	**Already congested**	**Charging During Congested**		**Mitigation**		**New Congestion**	
		Day-ahead	Imbalance	Day-ahead	Imbalance	Day-ahead	Imbalance
Schaep	13615	1.8%	**17.5%**	22.1%	11.6%	1.5%	8.4%
Monnickendam	5683	2.8%	**17.9%**	39.6%	27.0%	2.4%	15.6%
Zaandijk	1312	2.0%	16.2%	40.9%	**44.7%**	2.7%	**30.4%**
Kwadijk	246	0.0%	7.7%	38.2%	**87.4%**	1.6%	**30.1%**

Table 4.8: Congestion events under different load levels (2015–2024), split into day-ahead market vs. imbalance components. "Already congested" gives the absolute count, and all other entries are shown as a percentage of that baseline.

To analyze how the metrics of the time-constraint strategy change with substation conditions, the high-stress versus low-stress comparison was applied (Table 4.9). In high-stress MSRs the proposed time windows simply shut off the few remaining discharge events. Day-ahead relief falls by roughly one-third and imbalance relief by one-quarter. Moreover, new congested periods in the imbalance market decrease with respectively 6% and 2% for Monnickendam and Schaep. This shows that positive battery behavior drops further in percentages than the new congested periods. In low-stress MSRs, the same windows still allow batteries to mitigate 66% and 31% of baseline congestion in the imbalance market, while halving new congestion from about 30% to 16–19%. In these cases, time constraints effectively decrease congestion, while preserving most of the relief. Overall, time constraints fit the low-stress MSRs better than the high-stress MSRs in terms of the mitigation and new congestion ratio.

Scenario	Already congested	Charging During Congested		Mitigation		New Congestion	
		Day-ahead	Imbalance	Day-ahead	Imbalance	Day-ahead	Imbalance
Schaep (TC)	13615	1.1%	**6.8%**	8.7%	8.3%	1.0%	6.1%
Monnickendam (TC)	5683	1.5%	**8.3%**	25.8%	19.9%	1.7%	9.0%
Zaandijk (TC)	1312	1.4%	6.5%	23.2%	**31.1%**	1.9%	**15.7%**
Kwadijk (TC)	246	0.0%	4.9%	29.7%	**66.3%**	1.2%	**19.1%**

Table 4.9: Congestion events under different load levels with time constraints (2015–2024), split into day-ahead market vs. imbalance components. “Already congested” gives the absolute count, and all other entries are shown as a percentage of that baseline.

To conclude, the robustness analysis shows that, in general, the MSR outcomes of one station are not generalizable to other stations. Station-specific factors, such as load profiles and capacity of the MSR result in different findings. In practical terms, quantifying how R-BESS will influence congestion at a given MSR requires running the model separately for that station’s unique characteristics. However, day-ahead configurations offer more predictable control over congestion intensifying behavior, while imbalance-based operation is less robust in managing grid stress. These trade-offs must be carefully considered when designing future R-BESS market integration and implementing congestion-neutral strategies. More specifically, the specific power and capacity used in this thesis performs better in a MSR with a lower amount of already congested periods.

5 Discussion

This chapter discusses the key findings of this research and relates the modelling results to the literature review and the interview analysis. The study explored the interaction between R-BESS operation and local grid congestion, focusing on how congestion-neutral strategies can be designed to mitigate grid stress. Reflecting on quantitative modelling, stakeholder insights, and literature, this chapter analyzes the implications of the results, identifies limitations, and highlights opportunities for improving R-BESS integration. In particular, the discussion connects the technical results of the modelling with the literature and stakeholders' perspectives to show the societal and managerial relevance.

5.1. Research Findings

5.1.1. Grid Impact

Our quantitative modelling reveals that market-driven operation of R-BESS, particularly through participation in the imbalance market, can worsen grid congestion during peak periods. This result is consistent with previous studies that highlight the congestion risks resulting from uncoordinated battery storage activities, particularly when driven solely by financial incentives in imbalance markets (CE Delft and Witteveen+Bos, 2023; TenneT, 2025a). Our findings indicate that, for the day-ahead market, new congested events occur significantly during specific hours around noon. Moreover, day-ahead market trading has a positive mitigation effect during peak times, which was also concluded during the interview with CE Delft. However, for the imbalance market, new congested events and mitigation events occur throughout the day. This insight underscores the challenge of Alliander in restricting the R-BESS behavior. Moreover, it highlights observations by CE Delft (2025a), mentioning the challenges associated with implementing congestion-neutral strategies.

Our analysis also identified notable seasonal and time-specific patterns regarding grid congestion. Toward 2030, congestion is expected to extend beyond the traditional winter peaks into the summer months, occurring more frequently and at varying times throughout the day. This evolving congestion pattern underscores the critical need for flexible congestion management methods that can dynamically respond to changing demand and generation patterns. These findings align with stakeholder insights, emphasizing the urgency of adopting adaptive and responsive congestion-neutral strategies, where generic constraints will unnecessary mitigate positive effects of battery behavior. Such flexibility will become increasingly important to effectively manage grid reliability and operational efficiency with changing and increasing energy consumption trends and the increasing integration of RES.

The implementation of time constraints effectively mitigated congestion peaks. These constraints significantly reduced grid congestion, supporting the outcomes observed in the Zonneplan and Liander pilot project (Zonneplan, 2024). However, it also highlights the concerns of the opposition parties CE Delft and Essent. Both parties mentioned during the interviews that implementing time constraints is generic and that a more specific approach is needed to constrain the batteries effectively. The results namely underscore that day-ahead market batteries mitigate congestion during peak times, and constraining the batteries diminishes this value. Moreover, the overall energy system loses essential flexibility. A further recap of the interview analysis (Table 2.2) shows that Alliander plans to implement generic time constraints, while various actors expressed their criticism. Additionally, this research demonstrates the limited effectiveness of this strategy and the robustness analysis showed that the grid impact of one MSR cannot be generalized to another substation, highlighting the need for MSR-specific strategies.

The modelling also illustrates the load shaving of battery behavior to mitigate congestion, which is consistent with different studies (Nitsch et al., 2021; Plaum et al., 2022; Weckesser et al., 2021). However, these studies do not discuss the effect of load shaving. Load shaving due to introduced time constraints could result in higher peaks at other times, just outside the constrainted windows, which was addresses by Essent. The effect could be that mitigating congestion at some points could lead to higher peak times and eventually congestion at other moments.

Focusing on ToU tariffs, the results are in contrast to a research focusing on ToU tariffs from CE Delft, where a significant shift in behavior is illustrated (CE Delft, 2024). In this study, a minor shift in battery behavior was observed under ToU tariffs. However, this did not result into more mitigation events or less charging during congested periods or new congested periods. This difference can likely be attributed to the modelling approach. Whereas CE Delft simulated individual household behavior, this study focused on aggregated battery control at the portfolio level, with the aggregator optimizing for profit maximization. Furthermore, in the CE Delft study the day-ahead and imbalance markets were optimized by charging in the day-ahead market and discharging in the imbalance market. In this research, the two markets are decoupled. As a result, while ToU tariffs reduced overall profitability, they did not lead to substantial changes in battery operation patterns in the aggregated model. However, the results are consistent with another study from CE Delft (2025b). The aggregated behavior of R-BESS is similar to that of large consumers: no reduction in maximum capacity is observed. Although the CE Delft study identified a noticeable demand shift, our analysis did not reveal a shift of comparable magnitude. To conclude, both studies underscore that implementing ToU tariffs will not decrease the investment of DSOs in grid expansion.

5.1.2. Economic Feasibility

The economic analysis highlights that significant profits can be made with R-BESS application. This outcome is consistent with findings by CE Delft (2021) and Veenstra and Mulder (2024), mentioning that there is arbitrage potential in both the day-ahead and imbalance market. Moreover, published monthly results of R-BESS indicate their potential profitability in the imbalance market (Onbalansmarkt, 2025). However, it should be taken into account that exclusive reliance on these markets is increasingly unsustainable due to market saturation risks and regulatory constraints. Furthermore, insights from Essent indicated that regulatory hurdles, such as double taxation on stored and subsequently traded electricity, significantly hinder R-BESS investments.

Congestion-neutral strategies introduced large effects on profitability in the imbalance market. Time-based restrictions provided effective congestion mitigation but resulted in lower revenue potential due to restricted arbitrage opportunities. Moreover, ToU tariffs increased total system costs, aligning with the findings of Berenschot (2024a). In this research, an increase in total system costs implies a decrease in profit of the aggregator and the households. Building on these results, interviews with Alliander and Essent emphasized the need for regulatory support, including targeted subsidies and flexible incentive-based contracts, to effectively balance economic feasibility with grid security.

5.1.3. Sensitivity Analysis and Robustness

The sensitivity analysis demonstrated that the system is particularly sensitive to higher battery capacities, as the increase in capacity improved the revenue potential. However, a higher adoption rate of batteries was accompanied by a disadvantageous ratio of new and existing congestion relative to mitigation effects. This insight is critical for aggregators, as higher capacities can exacerbate congestion challenges, reducing the overall effectiveness of congestion-neutral strategies. Importantly, our analysis showed no significant change in grid impact from variations in energy tax ratios. This could be reasoned the same way as with ToU tariffs. As ToU tariffs show no shift in behavior with different tariffs, modelling on aggregator level is also not sensitive to changes in energy tax level because profit margins are still too high.

Robustness analysis indicated that the system is not robust under out-of-sample conditions, highlighting the limitations in generalizing the findings. In this context, “the system” refers to the model developed in this research, which represents the households, MSR, and the electricity grid. A lack of robustness should be interpreted as a lack of generalizability. In other words, the model outcomes observed for MSR Monnickendam do not necessarily apply to other MSRs, as they may yield significantly different results.

This lack of robustness aligns with actor interviews, notably those conducted with CE Delft and Essent, who both emphasized that congestion-neutral restrictions must be tailored specifically per MSR. CE Delft in particular also shared their concerns, where MSR specific is needed to implement congestion-neutral strategies, forecasting MSR load levels and restricting individually is not yet a feasible option. Consequently, this study reinforces the necessity for customized, localized strategies rather than general policies, as system output cannot be broadly generalized across different grid contexts.

5.2. Limitations

Several limitations should be acknowledged in interpreting the results of this research. First, the optimization approach employed in this study assumes perfect foresight of market prices, both for the day-ahead market and the imbalance market. While bidding strategies in the day-ahead market are determined 24 hours ahead, aligning reasonably with our modelling assumptions, real-world operations involve significant uncertainty, particularly concerning imbalance market prices. These prices are settled in real time every 15 minutes, presenting substantial forecasting challenges. Consequently, the perfect foresight assumption simplifies the complexities aggregators face when participating in these markets, potentially leading to an overly optimistic estimate of economic feasibility and operational efficiency. However, the model still shows what is theoretically possible, and therefore these insights are accordingly important for DSOs.

Secondly, the load profiles utilized in this study rely on the load from the MSR level to represent the household demand. While MSR data provides a practical representation of the cumulative demand across numerous households, it inherently smooths out individual variability. Individual household consumption typically displays much greater volatility due to varied usage patterns and behavioral differences. As a result, relying solely on aggregated MSR data might overlook critical peaks or localized variations, possibly leading to an underestimation of congestion issues at finer spatial scales.

Finally, this research primarily centers around a single MSR, Monnickendam, with additional robustness checks conducted across three other MSRs. Although this method provides valuable insights into localized congestion challenges and management strategies, it restricts the generalization of findings. Although robustness analysis in additional MSRs offers a degree of validation, it remains clear from our results and stakeholder interviews that congestion-neutral strategies need customized, MSR-specific evaluation. Consequently, general recommendations derived from this analysis must be interpreted within this localized context, emphasizing the necessity of targeted studies at each MSR level.

6 Conclusion

This thesis explored how congestion-neutral R-BESS can be integrated into the Dutch electricity grid to mitigate net congestion. In a context of growing electrification and increasing grid congestion, R-BESS present a promising, yet complex solution. However, whether they ultimately contribute positively or negatively to grid stability depends on how they are operated, controlled, and embedded within market and regulatory structures. This chapter concludes the study by answering the subquestions, synthesizing these insights into an overarching answer to the main research question, and reflecting on the broader implications for the Dutch energy transition.

6.1. Answering the Research Questions

Research Question 1

What are the key elements and processes that must be considered for the congestion-neutral integration of R-BESS in the Dutch electricity grid, based on insights from involved actors and literature?

The literature and stakeholder interviews confirm that the congestion-neutral integration of R-BESS is still in its early stages. While batteries are recognized as a valuable flexibility asset, their business case today remains largely driven by market incentives that do not account for local congestion patterns. A key element that needs to be taken into account is the goal of the R-BESS. If a household primarily uses its battery to store excess PV generation and is less focused on optimizing participation in the energy markets, congestion is unlikely to become an issue, and congestion-neutral strategies are generally unnecessary. Even more, the R-BESS shows a congestion reduction behavior, which is beneficial for the grid. However, a challenge arises when aggregators come into play, which pool residential batteries to meet market entry thresholds and optimize them for day-ahead and imbalance market participation. This optimization is currently performed without regard to whether battery actions might increase congestion on specific MSRs or other assets at higher voltage grids. The pool of batteries that react simultaneously on imbalance signals could worsen the grid stress and should be restricted. From stakeholder interviews, it can be concluded that DSOs should particularly focus on aggregators operating R-BESS. The reason is that aggregators with a portfolio containing only R-BESS, who still want to exploit significant return of investment, focus more on the imbalance market. Therefore, these parties have a larger impact on grid congestion.

DSOs and market experts emphasized that aggregator alignment with grid needs is essential. They highlighted the importance of institutional tools, such as time or location specific constraints and ToU tariffs, which can begin to steer battery behavior in a congestion-friendly direction. However, aggregators and CE Delft acknowledged that current implementations remain basic and that dynamic, location-specific steering will be required. This is in contrast to the decision-making party Alliander, who wants a generic congestion-neutral method that can be implemented across all MSRs. This decision is primarily justified by its relative ease of implementation compared to local and dynamic constraints.

Another key insight is that congestion patterns are highly local and dynamic. As stakeholders stressed, the behavior of one MSR cannot be assumed to represent others. As such, effective congestion-neutral integration in the MV grid will require station-specific modelling and close cooperation between DSOs and aggregators. Without such processes, batteries are risking to remain a new source of congestion rather than a solution.

Research Question 2

What is the impact of different R-BESS applications on grid impact and economic feasibility?

The modelling results reveal that R-BESS behavior varies substantially depending on the market strategy applied, with clear trade-offs between grid impact and economic feasibility.

First of all, seasonal patterns were significant. In 2024, congestion risks were concentrated in winter, but in the 2030 scenarios, congestion became more frequent across spring and autumn as well. In addition, peak congestion periods spread over more hours per day, complicating simple control strategies such as time constraints. In the 2030 scenarios, new congested periods also arise during night, which highlights the need to review the implemented congestion-neutral strategy during the upcoming years.

In pure day-ahead trading, batteries exhibited largely congestion-neutral behavior. They typically charged overnight and at midday and discharged during evening and morning peak demand. This pattern naturally mitigates grid stress and underscores the positive behavior of battery operation in the day-ahead market However, around noon, charging the battery introduces new congested periods, also showing the down side of unrestricted battery behavior. In contrast, when participants trade in the imbalance market, unpredictable price signals from the TSO drive much more volatile battery operation. Because those signals reflect neither household nor general company consumption patterns, they spread throughout the day. As batteries chase these signals without local grid awareness, they sharply increase charging during already congested periods. That behavior also generates new congested events, highlighting how difficult it remains to constrain imbalance-driven actions. Nevertheless, batteries still mitigate demand by discharging at high-peak times in the morning and late afternoon or evening, just as they do in the day-ahead market.

Value stacking, which combines day-ahead trading, imbalance market participation, and PV self-consumption, emerged from the modelling as the most balanced operational strategy. This is based on the lowest already congested periods, new congested periods and charging during already congested periods, next to a relatively high number of mitigation periods. This approach results in a more stable grid, particularly due to the feature of storing PV energy. In 2024, the intra-day analysis of battery operation revealed that under value stacking, new congested periods and charging during already congested periods remained largely limited, particularly in day-ahead dominant configurations. Batteries discharged effectively during the evening demand peak, when grid congestion is most critical, thereby providing valuable mitigation. Additionally, the introduction of PV significantly reduced net demand from the battery, as excess solar generation was stored locally and therefore the battery was charged behind the meter. Notably, under day-ahead trading, batteries did not contribute to new congestion during peak periods, a contrast to the imbalance market where volatile signals led to frequent charging precisely when the grid was under stress.

By 2030, as electrification progresses and seasonal congestion patterns broaden, value stacking focused on the day-ahead market continued to demonstrate alignment with grid needs. During the morning and evening peaks, the batteries provided significant mitigation through well-timed discharging. Although some new congested events occurred during night charging, the overall pattern remained grid-friendly compared to imbalance operation, which exhibited a more unpredictable profile. Moreover, the combination of value stacking with PV self-consumption helped to further stabilize battery behavior, ensuring that much of the charging activity occurred under neutral or beneficial conditions. In both years, the results clearly show that value stacking allows R-BESS to serve multiple system objectives: supporting self-consumption, capturing market value, and providing congestion mitigation. As markets become saturated and self-consumption gains value, value stacking emerges as an increasingly future-proof business model for aggregators. Interviews with various stakeholders indicated market saturation, noting that large-scale BESS will come to dominate the relatively small imbalance market. Moreover, value stacking arises as a more robust approach from the perspective of grid operators seeking to manage congestion.

In terms of economic feasibility, imbalance trading remained the most profitable strategy due to higher price difference potential. However, this came at the cost of increased congestion risks. Moreover, the saturation of the imbalance market should be taken into account. Value stacking provided somewhat lower revenues, but offered a much better trade-off between profitability and grid impact.

Research Question 3

What is the impact of integrating congestion-neutral strategies on grid impact and economic feasibility, and how robust are the results?

The modelling of time-based constraints and ToU tariffs provided clear insights. Time-based constraints, blocking battery operation between 12:00–14:00 and 17:00–19:00, were effective in reducing charging during congested periods and new congested events. However, they also reduced mitigation, and therefore diminishing the positive effects of the battery behavior and flattening the business case. Moreover, introducing time constraints underscored the concern of Essent, who mentioned that restricting certain windows would shift charge or discharge behavior just outside of those windows. The modelled scenarios show that the time constraints also limit peak shaving, meaning that batteries cannot always charge or discharge during short, high-demand windows. As the household is more dependent on electricity from the grid, peak shaving is less effective in this scenario.

In contrast, ToU tariffs had a limited steering effect. The price signals provided were not sufficient to prevent congestion-prone behavior. It should be noted that this is the result for battery behavior on aggregator level. CE Delft concluded that ToU tariffs could effectively improve grid stress for individual households. For that reason, there should be a distinction between restricting on the household level and on the aggregator level. supplementary agreement must include separate contract codes and billing rules. A household tariff for individual end-users, and an aggregator tariff, so that energy traded by aggregators is charged at a different rate. However, this approach could introduce administrative complexity.

The sensitivity analysis showed that increasing battery capacity beyond the threshold of 100% and below the threshold of 75% for PV capacity, the ratio of new congestion to mitigation increases. However, the battery behavior in this model is not sensitive to energy tax fluctuations. Finally, robustness testing revealed that battery behavior and congestion risks vary substantially across different MSR profiles. This confirms the stakeholder view that congestion-neutral strategies must be localized. One-size-fits-all approaches will not suffice, strategies must be framed per MSR.

Research Question

How can congestion-neutral R-BESS be integrated into Dutch electricity networks to mitigate net congestion while balancing techno-economic trade-offs?

The findings of this thesis demonstrate that R-BESS can support congestion management in the Dutch grid, depending on the time and energy market. Left to current market incentives, especially imbalance market trading, batteries risk becoming a significant source of new congestion and charging during already congested periods, particularly as integration scales up toward 2030.

Day-ahead value stacking (without imbalance and with PV) emerges as the most promising operational strategy, balancing profitability with grid supportive behavior. Batteries operating under this strategy tend to charge and discharge in ways that support grid stability, especially when combined with self-consumption of PV.

In the short term, time-based constraints are an effective way to enforce congestion-neutral operation. However, as grid stress evolves, becoming more seasonal, distributed, and time-varying, static time windows will not be sufficient. Dynamic congestion management tools, such as adaptive constraints or real-time grid signals, will be required to sustain congestion-neutral outcomes in the long term. Finally, localization is essential. This research confirms that grid impact is highly MSR-specific. Aggregators will need to implement location-aware control and DSOs must develop congestion maps to enable targeted strategies.

6.2. Recommendations

Based on the findings of this thesis, several key recommendations can be made to guide the effective integration of congestion-neutral R-BESS in the Dutch electricity system. These recommendations address both technical and institutional elements and reflect the evolving grid congestion patterns between 2024 and 2030.

MSR-specific modelling

Congestion-neutral integration should always be based on detailed modelling or monitoring at the MSR level. The results of this thesis clearly show that congestion patterns differ significantly across MSRs in both timing and severity. Uniform strategies are unlikely to be effective across the entire grid. Tailored modelling is required to design battery control strategies that align with local congestion dynamics and avoid unintended grid impacts.

Differentiated constraints for day-ahead and imbalance trading

It is recommended to apply different constraints to batteries that operate in different markets. Batteries trading in the day-ahead market exhibit naturally congestion-friendly behavior and require only soft constraints. In contrast, imbalance market trading carries much higher congestion risks due to volatile and unpredictable price signals. For these batteries, stricter steering measures are necessary to prevent charging or discharging during critical congestion periods. Furthermore, imbalance trading necessitates a higher maximum capacity for the MSR, so imposing stricter limits on imbalance trading could also reduce costs for DSOs. Limitation or steering contracts for large-scale BESS are better suited for providing imbalance services, since TenneT can dispatch them to specific grid locations and take congestion into account. However, we should implement these constraints without undermining the benefits of day-ahead trading. A practical solution is to use the mode selection into the household's application of their R-BESS. This option is already available to households whose aggregator is Essent or Zonneplan. There, users could choose between self-consumption, a passive day-ahead trading strategy, or an aggressive imbalance-trading strategy. If a household selects the aggressive imbalance mode, the R-BESS would automatically operate under tighter restrictions.

Continuous validation and updating of constraints

If static constraints are implemented, they must be continuously validated and updated to remain effective. This research demonstrates that congestion patterns evolve significantly between 2024 and 2030, becoming more seasonal and spreading over more hours of the day. Static time-based constraints that are effective today may not remain suitable under future grid conditions. DSOs and aggregators should adopt an adaptive approach, regularly refining constraint definitions based on updated congestion data.

Differentiating household-level and aggregator-level control

It is important to distinguish between household-level and aggregator-level battery operation. This distinction can be applied by focusing on different markets, as aggregators can trade in the imbalance market. Aggregator-controlled batteries that participate in imbalance markets can have a much greater impact on grid congestion and must be subject to explicit constraints and monitoring. Households cannot act on the imbalance market and therefore have a smaller impact on net congestion. Regulatory frameworks should reflect this distinction to avoid overregulation of R-BESS.

Reassess ToU tariffs and shift to direct congestion-neutral incentives

Static ToU bands are ineffective both for day-ahead and imbalance trading: in the day-ahead market they already mirror the battery's natural charging and discharging cycle. Namely being lowest at night and around solar noon. In the imbalance market the mean absolute percentage difference in shortage prices with and without ToU rounding is 0.1033%, indicating negligible impact. Rather than persisting with broad net tariffs that fail to change behavior, policy should focus on directly rewarding households for congestion-neutral operation. An example is financial compensation for congestion-neutral behavior. Such incentives will more effectively align R-BESS dispatch with grid needs than the current ToU tariffs.

Aligning market incentives

Current market designs do not adequately incentivize congestion-neutral behavior. In particular, the imbalance market encourages battery actions that can worsen congestion. Mechanisms such as compensation for congestion relief or market designs that reward a congestion-neutral quality mark should be further developed. Aligning market incentives with grid needs is critical to ensuring that R-BESS operate in a way that supports grid stability. While a GOPACS platform, now only used for HV networks, for MV networks could enable this, its complex implementation means it will not relieve congestion in the short term.

Strengthening cooperation between DSOs and aggregators

Finally, stronger cooperation between DSOs and aggregators is essential. Aggregators require access to grid data to align their control strategies with local congestion conditions. DSOs, in turn, need transparency regarding aggregator behavior to effectively monitor grid impacts. Establishing clear data-sharing protocols and strengthening collaboration between these parties will be key to enabling more dynamic and integrated congestion management solutions in the future.

In conclusion, by addressing these seven priorities, policymakers, DSOs, and market actors can lay the foundation for a scalable, sustainable, and grid-friendly future for R-BESS in the Netherlands.

6.3. Future Work

Although this thesis provides important insights into the congestion-neutral integration of R-BESS in the Dutch electricity grid, several aspects remain for further research. The following directions would allow for deeper exploration of battery-grid interactions, other modelling angles of future market environments, and more adaptive strategies for system integration.

Changing modelling objective

A promising direction for future work is to adjust the modelling objective. In this research, the objective function focused on minimizing total system costs. An alternative approach would be to shift the objective towards minimizing grid congestion, such as the number of congestion periods or peak transformer loading. This would enable a deeper understanding of how R-BESS can be steered explicitly as a congestion management resource, and what the trade-offs would be for aggregator revenues and system operation.

Optimizing the R-BESS characteristics

Following up on the previous suggestion, optimization of R-BESS adoption rate, capacity, and power should be integrated within the modelling framework to identify the configurations that maximize congestion mitigation while minimizing both new congested periods and charging during existing congestion. Multi-objective optimization algorithms can optimize the grid support metrics and the optimal R-BESS. The resulting station-specific guidelines will link adoption rate, capacity, and power ratings directly to expected mitigation performance and congestion risk, thereby enhancing the practical applicability and generalizability of the model outcomes.

Including other energy markets

Future research could also expand the market scope of the model. The current work focuses on the day-ahead and imbalance markets. However, markets such as the FRR and congestion markets will likely become increasingly relevant for battery operation. Including these markets would allow for a more complete analysis of future revenue stacking strategies and their interaction with local congestion patterns.

Dynamic congestion signals and real-time control

Another important direction is the development of dynamic congestion signals and real-time control mechanisms. In this research, static time-based constraints and ToU tariffs were used to enforce congestion-neutral behavior. However, as congestion patterns evolve between 2024 and 2030, more dynamic approaches will be required. Future work should explore how real-time congestion signals from DSOs can be integrated into aggregator control strategies, enabling more adaptive and precise congestion management.

Agent-based modelling of household behavior

To further increase the realism of the model, future studies should incorporate, for example, ABM to represent heterogeneous household behavior. In this research, the aggregator was assumed to steer all batteries uniformly. In practice, households will have different preferences, contract types, and control capabilities. ABM would allow for the exploration of how such heterogeneity affects system-level outcomes and whether certain types of behavior increase or mitigate grid congestion risks.

Detailed distribution grid modelling

Moreover, more detailed distribution grid modelling, particularly at the HV level, would be highly valuable. This research focused on the MSR level, but many congestion issues originate in the HV grid as well. Many new residential developments and commercial sites connect directly via MV or HV feeders, so congestion can originate above the MW network.Integrating HV models would provide a more comprehensive understanding of how R-BESS impacts grid performance at all voltage levels and would help DSOs target flexibility where it is most needed.

Incorporating more diverse MSR data

Finally, the research reveals that insights drawn from a single MSR cannot simply be transferred to others. It was observed that these seasonal differences led to different responses to congestion-neutral strategies, and resulted in other output for mitigation, charging during already congested periods and new congested periods. To build broadly applicable recommendations and to convince DSOs of the value of portfolio level control, a richer dataset is needed. Future work should model a variety of MSR locations with different load shapes, peak timings, and network constraints. In particular, exploring in more detail how the benefits of congestion mitigation measures shift as substation conditions change would uncover the key drivers of strategy performance.

6.4. Academic Reflection

This research's limitations not only bound its findings but also highlight promising opportunities for future work. First, the perfect-foresight assumption for both day-ahead and 15-minute imbalance market prices, could present an overly idealistic scenario. Future work should therefore adopt stochastic or robust optimization frameworks to capture the substantial uncertainty aggregators face, particularly in the imbalance market. Second, reliance on MSR-level load profiles smooths out individual household volatility and may underestimate localized congestion peaks, suggesting a need to move toward higher-resolution or agent-based models of heterogeneous household behavior to uncover how behavioral diversity shapes congestion outcomes. Finally, this study's focus on a single MSR, with robustness checks on three others, limits broad generalizability: an expanded multi-MSR, would improve the understanding of congestion-neutral designs.

Despite these limitations, this work makes several novel contributions to both the academic literature and the evolving political debate. To date, no scientific studies have explicitly addressed congestion-neutral operation of residential battery storage, underscoring the originality of this thesis's mixed-methods framework combining stakeholder-driven qualitative insights with PyPSA-based MILP simulation. Politically, it arrives as congestion-neutral R-BESS gains prominence in Dutch strategic planning: the Regional Energy Strategies publication elevates distributed flexibility in early 2025 (National Program RES, 2025), a parliamentary letter from the Ministry of Economic Affairs and Climate Policy underscores the need for such batteries (Rijksoverheid, 2025b), and a follow-up letter highlights the absence of implementation guidance (Ministry of Economic Affairs and Climate, 2025a).

By outlining the impact of congestion-neutral R-BESS operation on grid impact and economic feasibility, this thesis establishes an scientific understanding for bringing congestion-neutral R-BESS into practice. Future studies can build on this foundation by: redefining the optimization goal to directly target reductions in congestion events or peak transformer loading; expanding the market scope to include reserve services and congestion markets; designing and testing real-time congestion signals; incorporating detailed low-voltage grid representations; and modelling a diverse portfolio of substations to establish overarching guidance for R-BESS specific operation.

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A

Rationale for Focusing on R-BESS

What makes energy storage systems a particularly attractive solution among the available options? To address this, Schmidt and Staffell (2024) identifies four core concepts essential for enabling energy system flexibility. Next to electricity storage, Schimdt and Staffel identify flexible generation, network interconnection and DR. Where flexible generation and network interconnection are both technical strategies. Moreover, DR is a behavioral strategy, but could also be obtained by market-based strategies.

A.1. Demand Side Management

To decrease peak times in the Dutch grid, DR is seen as a potential method to support the grid (Rouwhorst et al., 2020). However, limitations arise from the the unpredictable behavior and decision-making of consumers. One of the biggest obstacles is the general lack of awareness and understanding of electricity markets. Many consumers are unfamiliar with concepts like kilowatt-hours, peak demand, and time-of-use pricing, making it difficult for them to recognize the benefits of adjusting their energy consumption (Torriti et al., 2010). Utilities often fail to effectively promote DR programs, further contributing to low participation rates. Another challenge is the limited availability of smart meters and other enabling technologies. These devices are essential for real-time monitoring and automatic response to price signals, but their deployment is slow due to high costs and a lack of incentives. Even when such technology is available, consumers often struggle with accessing and interpreting real-time usage data (Brohmann et al., 2009). Without clear and convenient information, many find it difficult to modify their consumption behavior. DR programs also require consumers to actively monitor and shift their electricity usage based on changing prices. This shift from a passive to an active role can lead to response fatigue, where consumers grow tired of constantly adjusting their routines (Watson et al., 2002). Many who initially sign up for time-of-use pricing later revert to fixed-rate plans due to the inconvenience (Kim and Shcherbakova, 2011). The financial aspect also plays a role. While DR can lead to cost savings, electricity bills make up a small percentage of household expenses. The perceived financial benefits may be too small to justify the effort, especially when upfront costs for smart meters and automation devices are involved (Torriti et al., 2010). Beyond financial and technical barriers, consumers passive behavior further limits adoption. Many people stick with their current energy provider and pricing model simply because switching requires effort and the potential benefits seem uncertain (Breukers et al., 2011). Research in different Western countries underscore this insight as a obstacle towards DR (Kim and Shcherbakova, 2011). These insecurities make it harder to implement DR, and therefore electrical energy storage is preferable (Alanne and Saari, 2006; Niemi et al., 2012). This implementation will ultimately lead to higher energy security (Khan et al., 2018).

Moreover, battery energy storage systems (BESS) are well-established and scalable technologies. However, their deployment may increase local grid load, particularly when users respond to high imbalance market prices, potentially leading to local congestion. This issue has been examined in several recent studies (CE Delft, 2023a; TenneT, 2023; Stedin, 2025). A first congestion-neutral strategy is introduced, where BESS are restricted to charge or discharge during peak demand and supply. BESS are still regarded as a high-potential solution for addressing net congestion by the TSO and DSOs. As well, Abdisalaam et al. (2012) highlight the importance of storage solutions. The article researched the potential cost reductions for residential customers when implementing DR. In this case, benefits of DR were based on price votality. However, as more households participates the price votality flattens and thereby the potential benefit. It was concluded that demand response can only be interesting as a business case when energy storage options are not available within an area.

A.2. Flexible Generation

Another method to decrease net congestion is flexible generation. Flexibility in power systems refers to the ability of power plants to intentionally adjust their output. This has always been essential, as electricity supply must continuously balance demand, which fluctuates on an hourly, daily, weekly, and seasonal basis. Currently, around 80 percent of this flexibility is provided by gas, coal, and hydro power. However, as the reliance on gas and coal decreases and hydro is not a viable option in the Netherlands, alternative flexibility solutions are needed. The increasing share of non-dispatchable energy sources, such as wind and solar, further intensifies the demand for flexibility in power systems. Fortunately, significant reductions in battery storage costs are unlocking new opportunities to enhance system flexibility (International Energy Agency, 2018). However, while battery storage is not yet widely used, curtailment is used to address overproduction. This will lead to energy waste and therefore it can be argued that this should be prevented (Braat et al., 2021). Bird et al. (2016) predict that the amount of curtailed energy will in crease in North-east Europa from 0.4 TWh in 2020 to 9.3 TW h in 2030. EES could prevent curtailment by reloading during overproduction and unloading when demand exceeds supply.

A.3. Network Interconnection

The last strategy for a flexible energy system is network interconnection and expansion. Expanding the network by increasing interconnections between regions with diverse weather patterns is considered a cost-effective solution (MacDonald et al., 2016). In 2023, the largest European tender of €30 billion was signed to ensure security of supply. Next to grid expansion, TenneT invests significant amounts in interconnection research between North-European countries. Nevertheless, as mentioned in the problem statement, a major part of the country is congested, therefore interconnection is not an option. As well, Germany faces several challenges regarding grid congestion due to large windparks. As grid expansion will take several years, storage options are envisioned as methods to mitigate congestion in the short-term and in the long-term (TenneT, 2024a) To tackle net congesiton more effectively, the government focuses on the ”Landelijk Actieprogramma Netcongestie (LAN)”. In this program, the government works closely with grid operators to create a larger, more efficient and flexible infrastructure. 15000 stations have to be increased in size by 2030. However, the government and grid operators conclude that even with adjustments and significant investments, grid congestion will remain a challenge in the coming years and after 2030. Flexible capacity could partly address this challenge with ESS, where the main focus is battery energy storage systems (Ministry of Economic Affairs and Climate, 2023).

A.4. Battery Energy Storage Systems

The integration of BESS is becoming increasingly important as the Netherlands advances its energy transition. As electrification grows, the need for both large-scale and small-scale energy storage solutions increases. Technologies such as compressed energy storage, hydrogen storage, and especially BESS are expected to play a significant role in ensuring energy system flexibility by 2030 and 2050 (Sijm et al., 2020). Due to their reliability, operational flexibility, and anticipated cost reductions, BESS is considered a high-potential technology for the Dutch grid (Telaretti and Dusonchet, 2017; Zubi et al., 2018). Their ability to provide services like load smoothing and loss minimization further adds to their attractiveness (Farrokhifar et al., 2013).

The technical and economic feasibility of BESS integration is well supported in literature (Gallo et al., 2016; Sabihuddin et al., 2015). This is exemplified by a €350 million project in the Netherlands that aims to become one of Europe’s largest battery storage systems, capable of supplying electricity to 200,000 households (Energy Storage NL, 2025).

A study by Kalavasta, commissioned by Energy Storage NL, highlights the value of BESS, estimating that these systems could reduce overall system costs by more than €300 million (Kalavasta, 2024). This cost saving is achieved through multiple channels: households and businesses can benefit from electricity price volatility, while grid operators can reduce costs on imbalance markets and reserve capacity.

The growing relevance of BESS is further reinforced by increasing political and regulatory support in the Netherlands. Key incentives include exemptions from energy taxes for both home and large-scale batteries, as well as reduced grid tariffs. However, the latter subsidy currently applies only to front-of-the-meter storage systems and is therefore not applicable to R-BESS (ACM, 2024b; Rijksfinanciën, 2021).

Despite these promising developments, local grid congestion remains a pressing issue. While BESS can offer significant flexibility benefits, their uncontrolled use may also contribute to congestion. The concept of BESS contributing to congestion will be elaborated in the state-of-the-section. To tackle this challenge, the concept of congestion-neutral battery operation is therefore gaining attention. As it remains relatively new, further research is needed to understand its practical implications and to develop strategies for integrating BESS in a manner that supports the grid.

B

Imbalance Market

In the Dutch electricity balancing market, TenneT determines the imbalance price based on the system's regulation state, which indicates whether upward and/or downward regulation is needed within a 15-minute Program Time Unit (ISP). Different rules apply depending on whether there is a net shortage (consumption) or surplus (injection) in the system. When no incident reserve is activated, TenneT relies on accepted regulating bids,sometimes combined with a reference mid price to calculate the imbalance prices.

The mid price (P_{mid}) is defined as the average of the lowest accepted upward regulating bid and the highest accepted downward regulating bid. This neutral value is particularly relevant when both upward and downward regulation are activated during the same ISP.

When no regulating power is activated and the system is balanced:

- Imbalance price (shortage and surplus) = P_{mid}

If only upward regulation is activated (due to energy shortage):

- Imbalance price (shortage) = P_{up}
- Imbalance price (surplus) = P_{up}

No mid price or incentive component is used, as the system needs additional supply and both sides are settled at the cost of that supply.

If only downward regulation is activated (due to energy surplus):

- Imbalance price (shortage) = P_{do}
- Imbalance price (surplus) = P_{do}

Here, the prices reflect the cost of reducing injections, with no mid price or corrections applied.

When both upward and downward regulation occur simultaneously: This reflects a non-directional system imbalance. In such cases, TenneT applies corrections using the mid price to prevent distortion:

- *Downward regulating price (P_{do}):*
  - If $P_{\text{do}} \leq P_{\text{mid}} \Rightarrow P_{\text{do}}$
  - If $P_{\text{do}} > P_{\text{mid}} \Rightarrow P_{\text{mid}}$
- *Upward regulating price (P_{up}):*
  - If $P_{\text{up}} \geq P_{\text{mid}} \Rightarrow P_{\text{up}}$
  - If $P_{\text{up}} < P_{\text{mid}} \Rightarrow P_{\text{mid}}$

These corrections ensure that regulating prices do not deviate excessively from a neutral reference and help avoid reversed pricing, where surplus parties could be rewarded more than those facing a shortage. No incentive component is used unless further correction is required.

C

Interview Questions

This appendix provides the standard question set used for the semi-structured interviews conducted during this research. The interviews were structured around general questions applicable to all stakeholders, followed by stakeholder-specific questions tailored to their role in the energy sector. Objectives are listed for each question to clarify their intended purpose.

General Questions (All Stakeholders and Experts)

1. How do you see the role of household batteries in the current and future energy system?
   Objective: Gain insight into expectations and ambitions regarding battery integration in the energy market.
2. What are the key benefits and challenges of integrating battery energy storage systems (BESS) at different scales (household vs. large-scale)?
   Objective: Compare perspectives on small-scale vs. large-scale storage.
3. Which current policies or market mechanisms hinder the business case for household BESS, and why?
   Objective: Identify regulatory and economic barriers to battery deployment.
4. How do you foresee the impact of the phasing out of net metering on household battery adoption?
   Objective: Understand stakeholder assessments of regulatory changes.
5. What is your view on the congestion-increasing effects of batteries, and how can congestion-neutral constraints be effectively implemented for BESS? Which instruments are needed?
   Objective: Explore strategies to ensure BESS deployment aligns with grid stability goals.
6. How do you prioritize behind-the-meter battery storage compared to other congestion management strategies?
   Objective: Assess stakeholder priorities regarding BESS in grid management.
7. What is your vision on aggregators and their role in the imbalance market?
   Objective: Understand perspectives on the role of aggregators in battery operation.
8. From a technical perspective, do current battery solutions meet market needs in terms of storage capacity, efficiency, and cost?
   Objective: Assess the readiness and competitiveness of existing battery technologies.
9. Which revenue stream do you see as most promising for household BESS in the future?
   Objective: Identify future opportunities for battery profitability.

Stakeholder-Specific Questions

Research Institution

1. What are the main barriers to a viable business case for household batteries in the Netherlands?
   Objective: Identify economic and policy obstacles affecting adoption.
2. Can you elaborate on your recent report regarding low-voltage grid congestion driven by short-term market incentives?
   Objective: Understand interventions to implement R-BESS congestion-neutral.

3. Which incentives or regulatory changes do you believe would most effectively promote congestion-neutral household batteries?
   Objective: Identify policy recommendations based on research.

DSO

1. From your perspective, what is the ideal role of battery storage in managing grid congestion?
   Objective: Understand DSO expectations regarding BESS integration.
2. What lessons have been learned from past congestion management pilots involving battery storage?
   Objective: Gain insights from real-world projects.
3. How can DSOs ensure that household battery storage solutions are congestion-neutral rather than increasing grid issues?
   Objective: Explore their approach to preventing congestion increases.
4. Do you foresee a larger role for DSOs in directly managing or incentivizing battery storage deployment and regulating congestion-neutrality constraints?
   Objective: Assess their strategic vision for BESS integration.
5. What power factor do you typically use for household battery connections?
   Objective: Obtain a reference value for modeling purposes.

Aggregator

1. What is the biggest challenge in selling household batteries in the current Dutch market?
   Objective: Identify business and consumer-related barriers.
2. What role do aggregators like Zonneplan play in maximizing the economic potential of household batteries?
   Objective: Explore the value proposition of aggregation for small-scale storage.
3. What lessons were learned from the congestion pilot with Liander, and how can they be applied to future battery integration?
   Objective: Gain insights from real-world implementations.
4. To what extent do you directly control the batteries in terms of market participation and congestion neutrality?
   Objective: Understand the operational strategies for BESS control.
5. How can Zonneplan ensure that its battery solutions are congestion-neutral?
   Objective: Understand their strategies for congestion management.
6. What are the current market standards for battery efficiency, capacity, and pricing?
   Objective: Understand the technical and economic benchmark for household BESS.

D Research Flow Diagram

This appendix presents a visual representation of the research process used in this thesis. The diagram illustrates the sequential and iterative steps undertaken to answer the main research question and its correspodning subquestions. The process is divided into five key research phases. Each phase is linked to one or more subquestions, which collectively contribute to answering the main research question. The figure offers an overview of the inputs, processes, outputs, methods, and corresponding subquestions for each phase of the research.

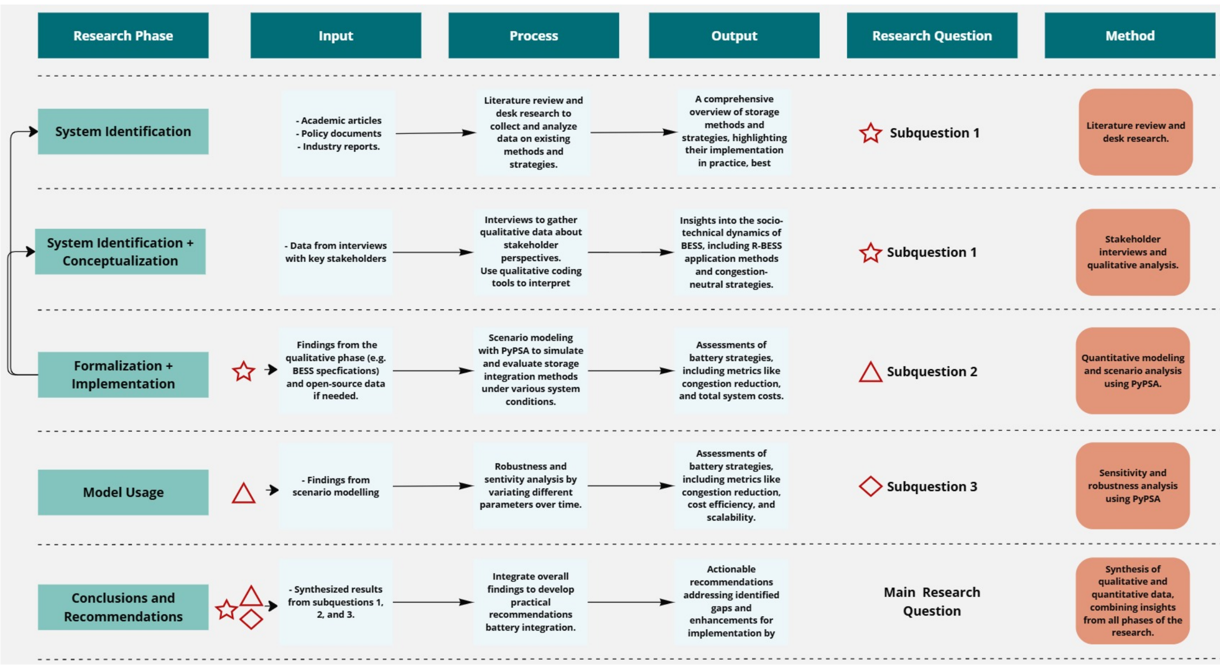

Figure D.1: Visualization of the research process.

E
Scenario Layers

To evaluate the impact of residential battery storage on grid congestion and economic feasibility, a layered scenario framework was developed. This appendix presents an overview of the different scenario dimensions that were combined to systematically analyze R-BESS behavior under various conditions. Figure E.1 provides a schematic representation of these layers. The scenario design is structured around six dimensions. By layering these scenario components, the research captures a broad composition of possible futures and battery control strategies. This approach enables a detailed comparison of trade-offs between congestion mitigation and economic viability under different policy and system conditions.

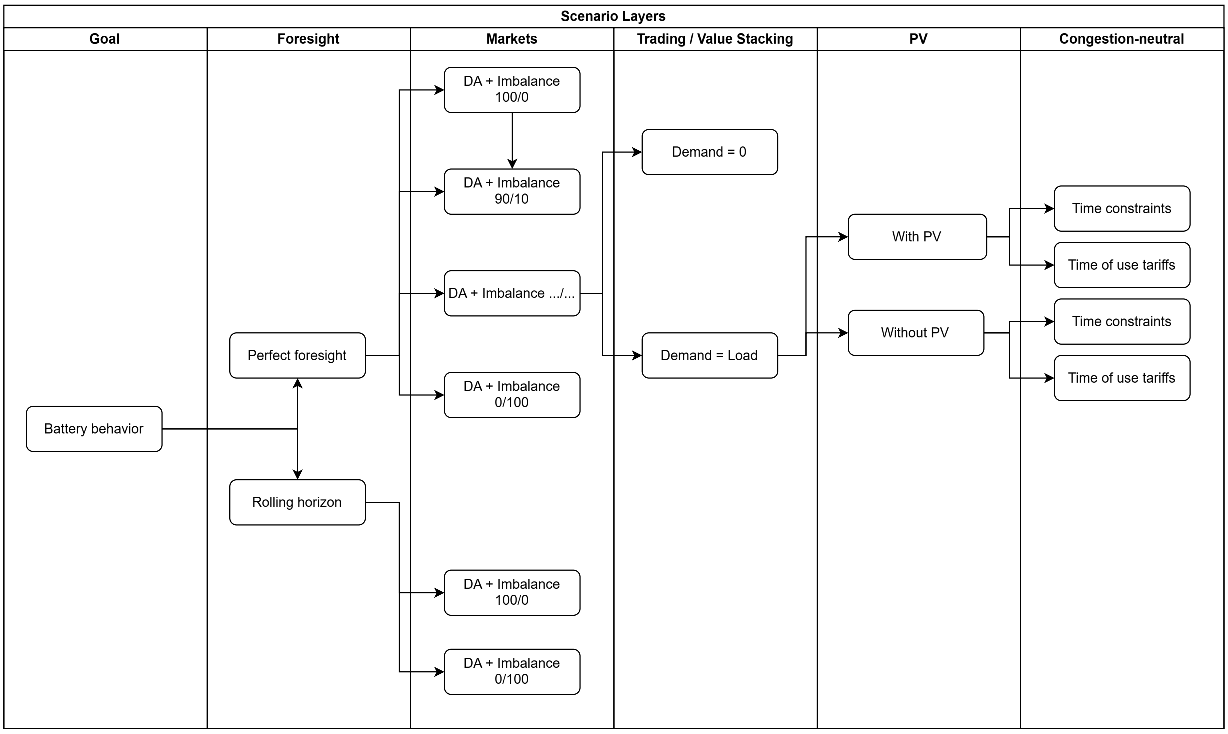

Figure E.1: The different layers of the scenarios used in this research.

F

Additional Results

This appendix provides supplementary analyses and visualizations to expand upon the insights presented in the main report. It includes additional results that focus on several key aspects, including a rolling horizon analysis that examines the robustness of optimization strategies, annual and seasonal congestion impacts across different scenarios, and detailed charging behaviors of R-BESS. Furthermore, analyses of household net load profiles are presented to illustrate the impacts of value stacking and congestion-neutral strategies. The appendix also includes an in-depth exploration of congestion events and their variations for the years 2024 and 2030, as well as detailed congestion heatmaps for 2030, highlighting temporal patterns of congestion events across various market participation ratios. For a comprehensive interpretation of these figures and detailed discussions, consult the corresponding sections in Chapter **??**=[e main report.

F.1. Rolling Horizon

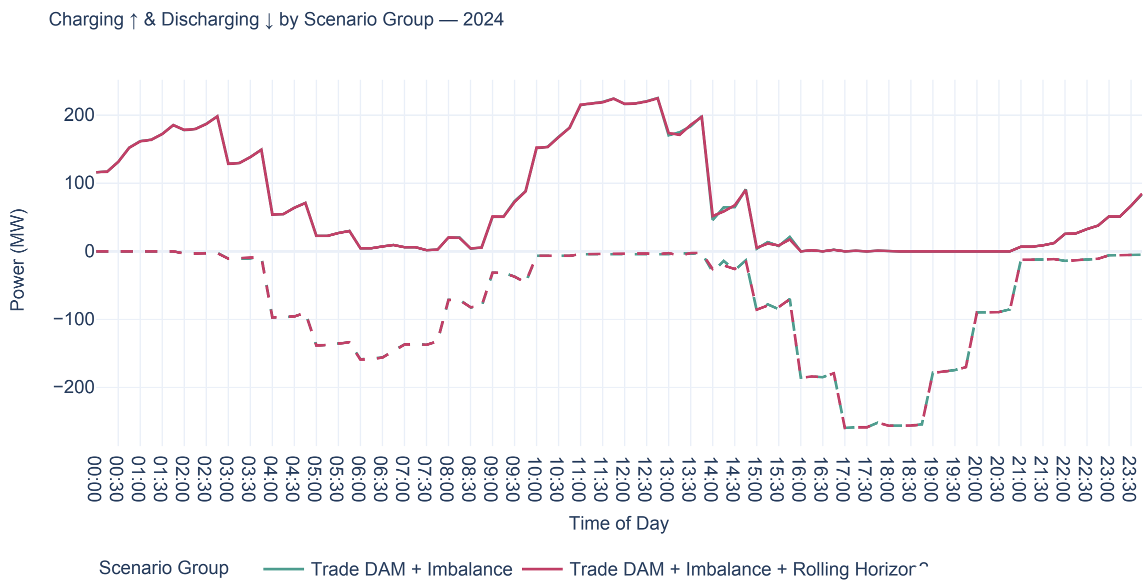

Figure F.1: Rolling horizon output for the day-ahead market. Showing no significant differences between rolling horizon and perfect foresight. The dashed line represents discharging behavior of the scenarios.

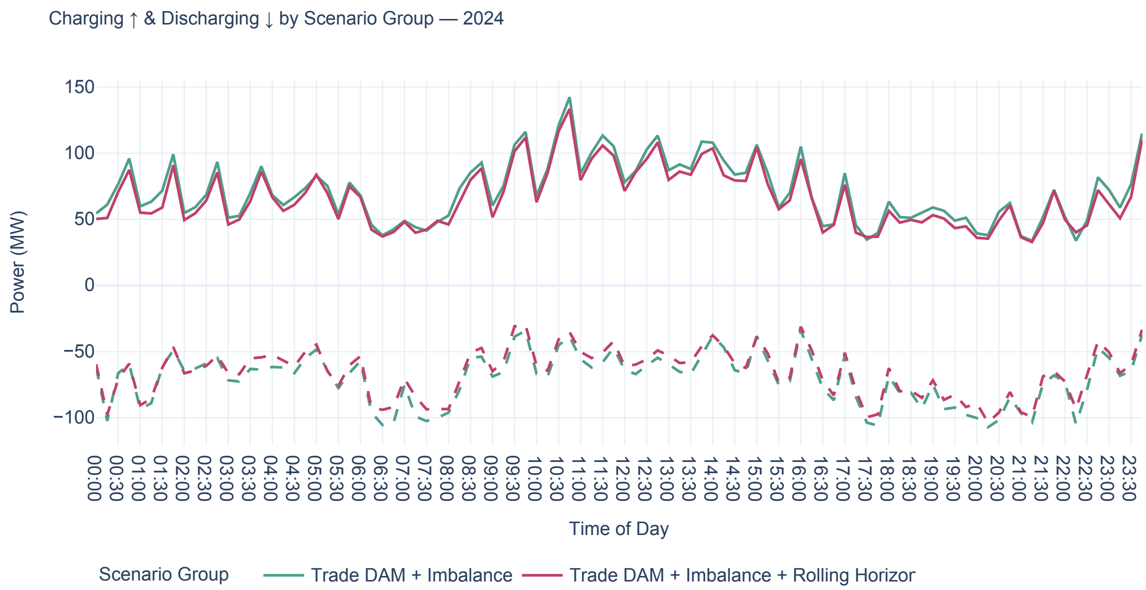

Figure F.2: Rolling horizon output for the imbalance. Showing little differences between rolling horizon and perfect foresight. The dashed line represents discharging behavior of the scenarios.

F.2. Seasonal Patterns Resulting from Battery Behavior

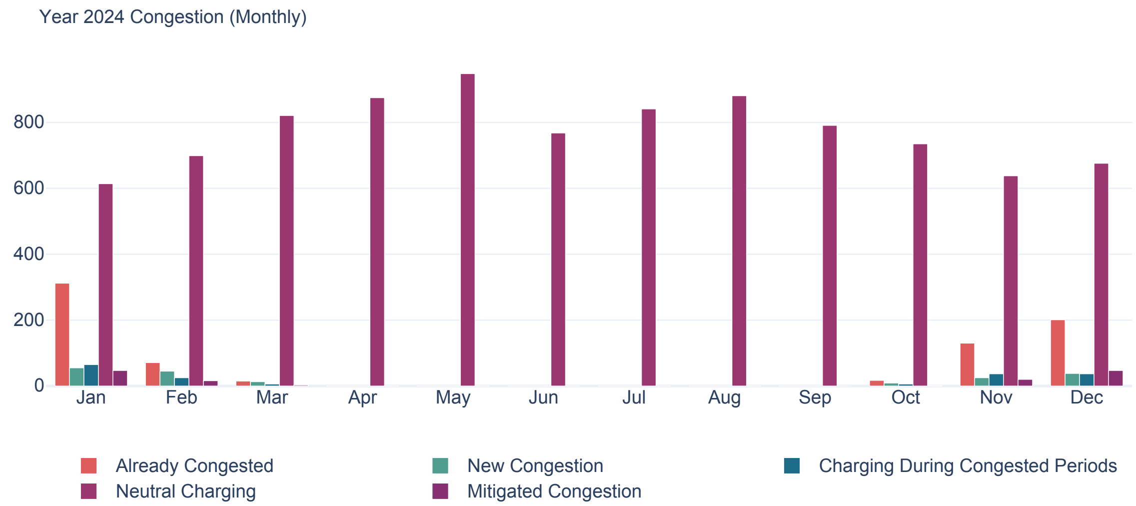

Figure F.3: Seasonal behavior and grid impact of the R-BESS in 2024 for the trade scenario in the imbalance market.

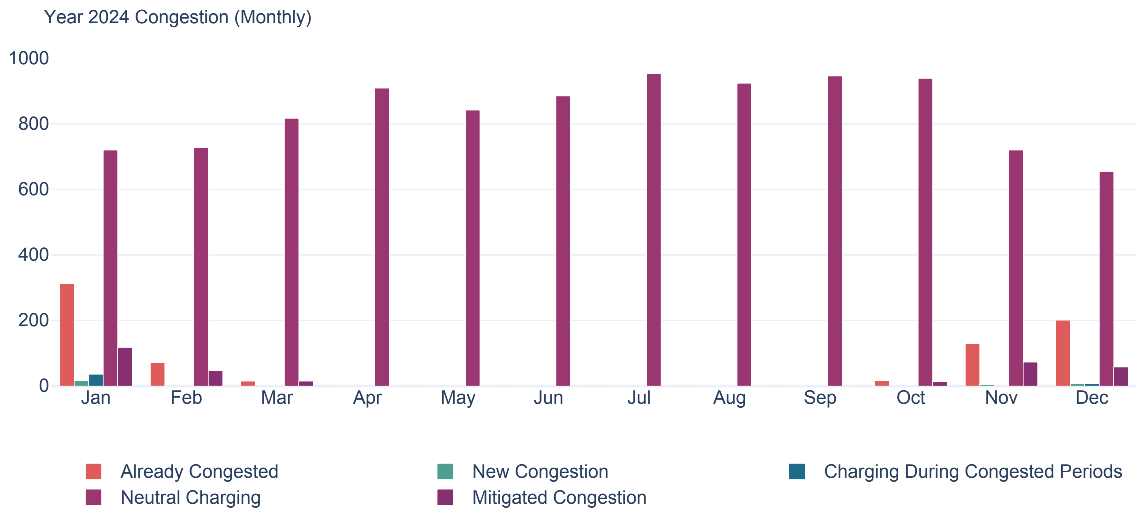

Figure F.4: Seasonal behavior and grid impact of the R-BESS in 2024 for the value stacking scenario in the day-ahead market scenario.

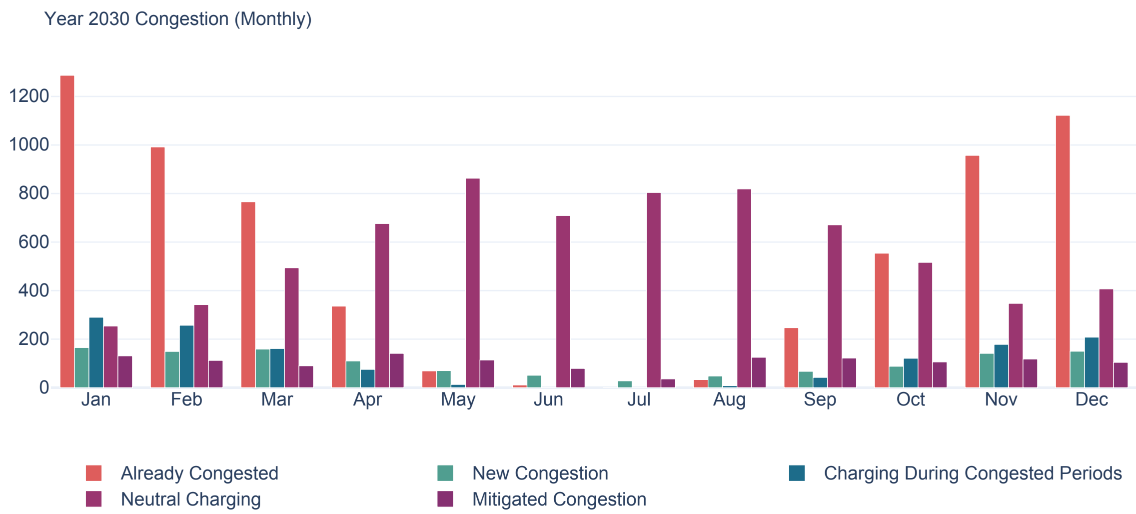

Figure F.5: Seasonal behavior and grid impact of the R-BESS in 2030 for the value stacking scenario in the imbalance market.

F.3. Charging Behavior

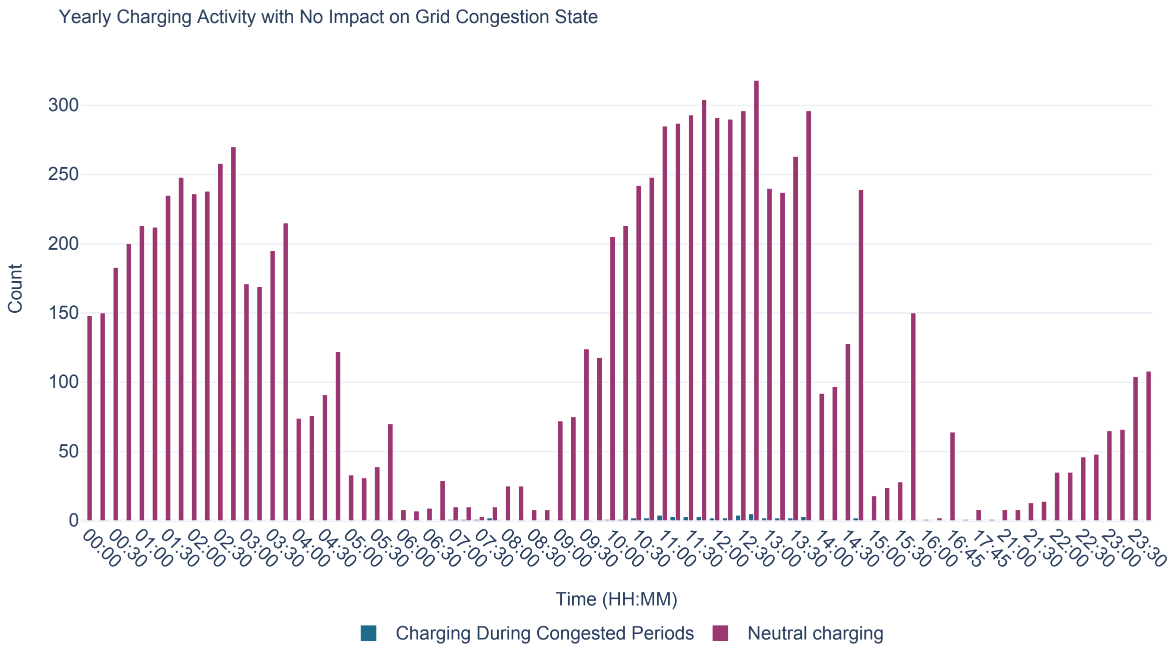

Figure F.6: Visualization of the charging behavior which occurs during already congested periods or neutral charging periods. The corresponding scenario is the trade scenario with 100% day-ahead market trading in 2024.

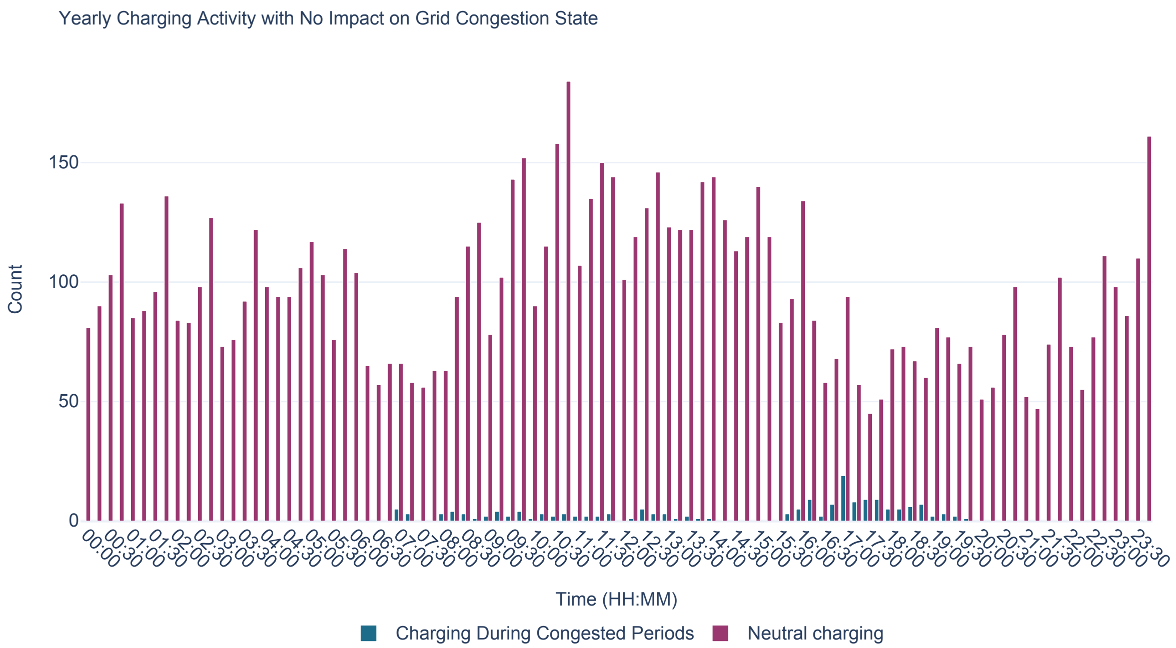

Figure F.7: Visualization of the charging behavior which occurs during already congested periods or neutral charging periods. The corresponding scenario is the trade scenario with 100% imbalance market trading in 2024.

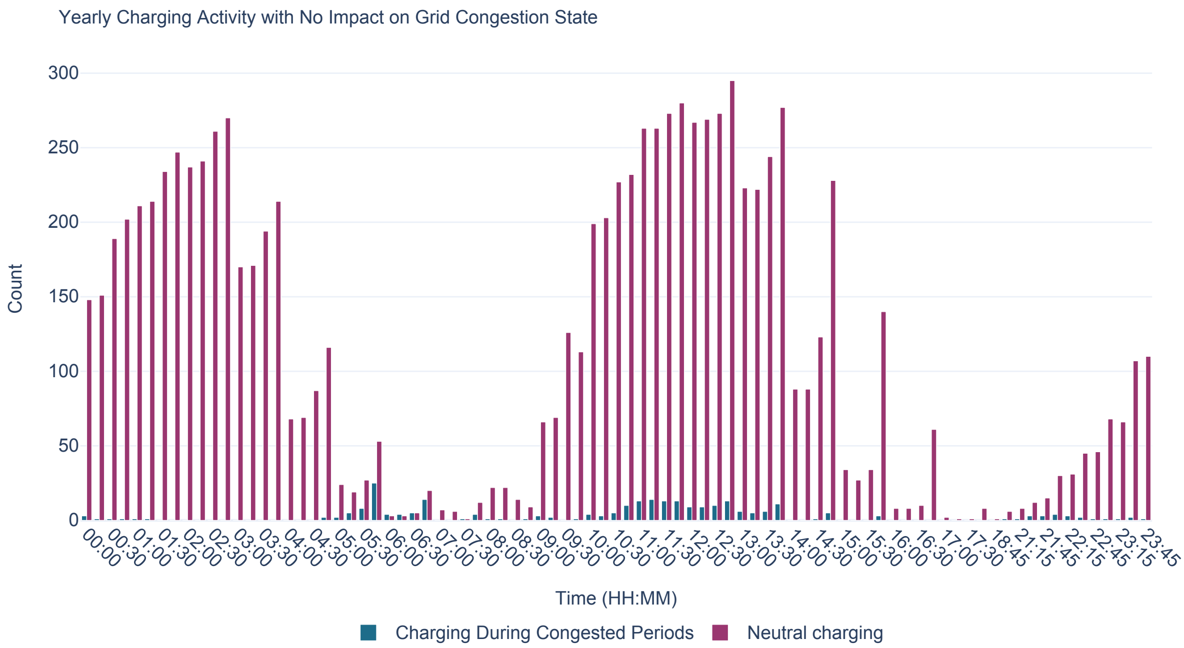

Figure F.8: Visualization of the charging behavior which occurs during already congested periods or neutral charging periods. The corresponding scenario is the trade scenario with 100% day-ahead market trading in 2030.

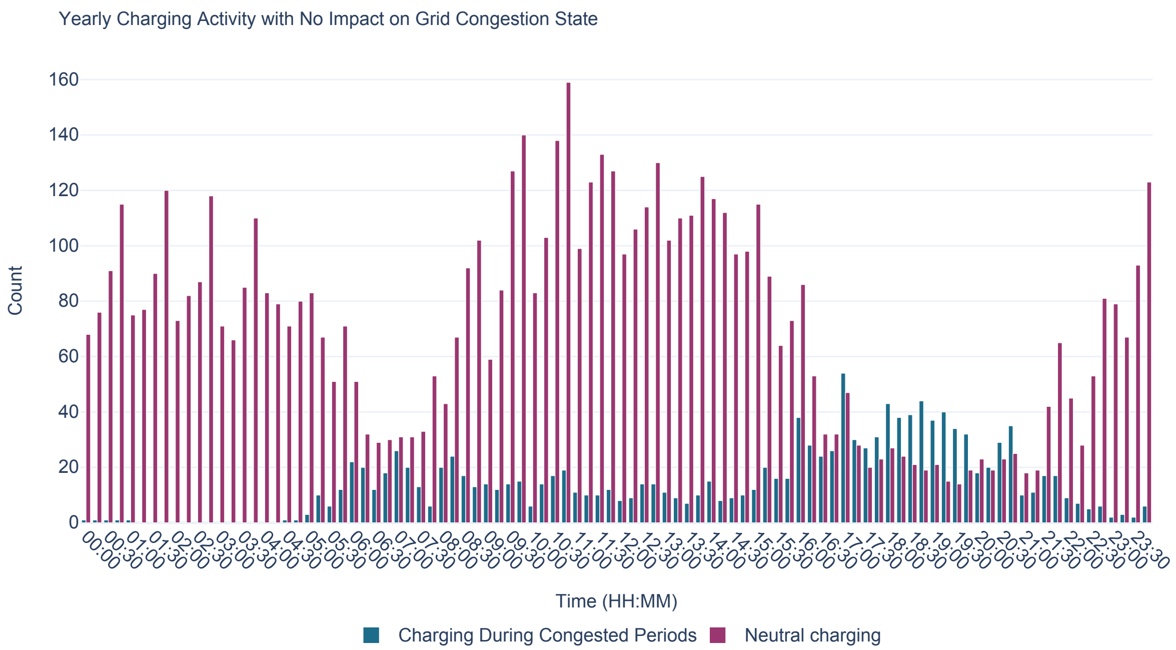

Figure F.9: Visualization of the charging behavior which occurs during already congested periods or neutral charging periods. The corresponding scenario is the trade scenario with 100% imbalance market trading in 2030.

F.4. Energy Flow to Household

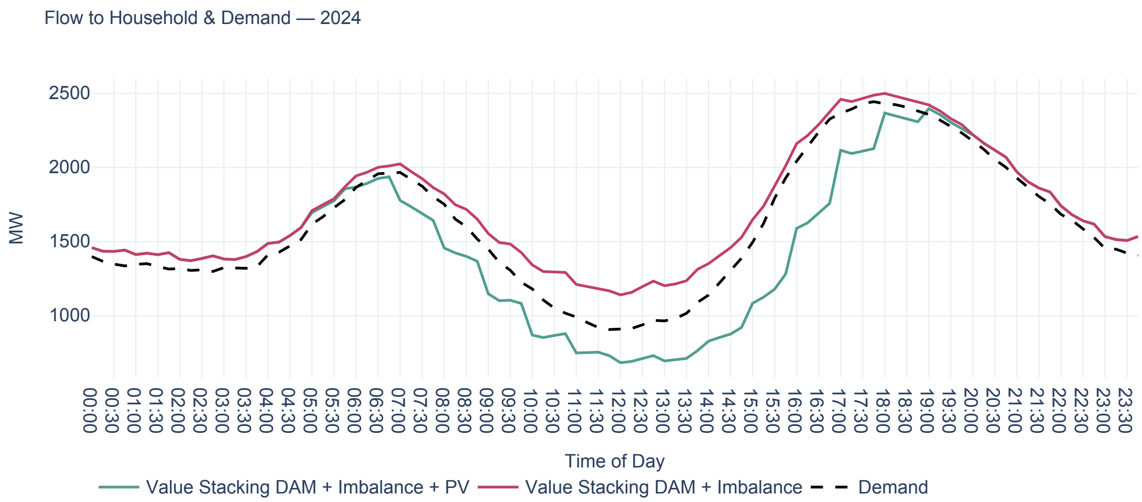

Figure F.10: The difference in load levels between a network with extra PV or without (imbalance market).

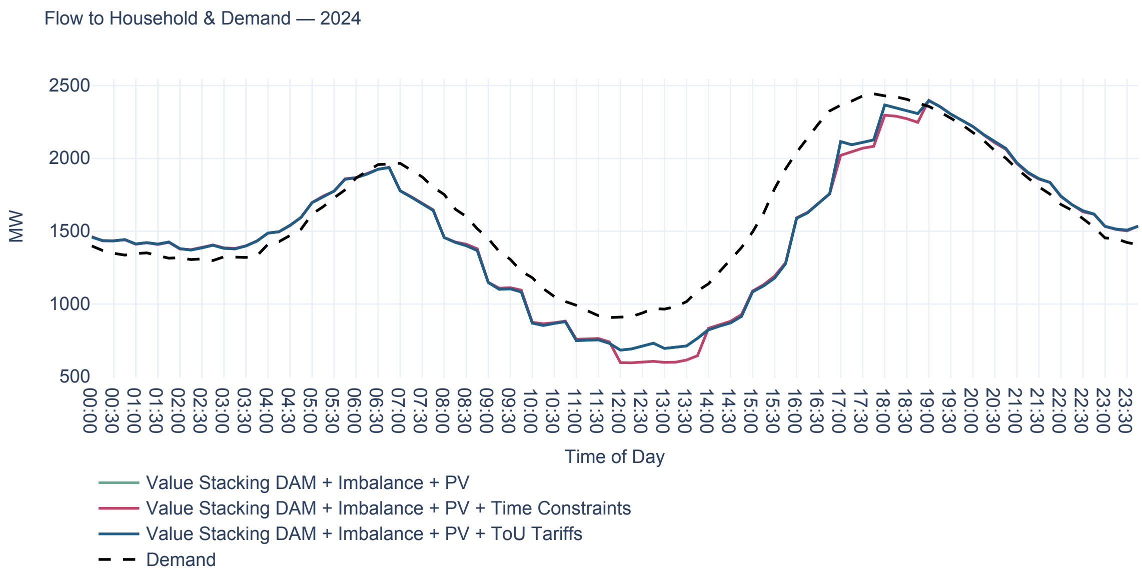

Figure F.11: Impact of congestion-neutral strategies on household net load profile across the day (imbalance market).

F.5. Events 2024 + 2030

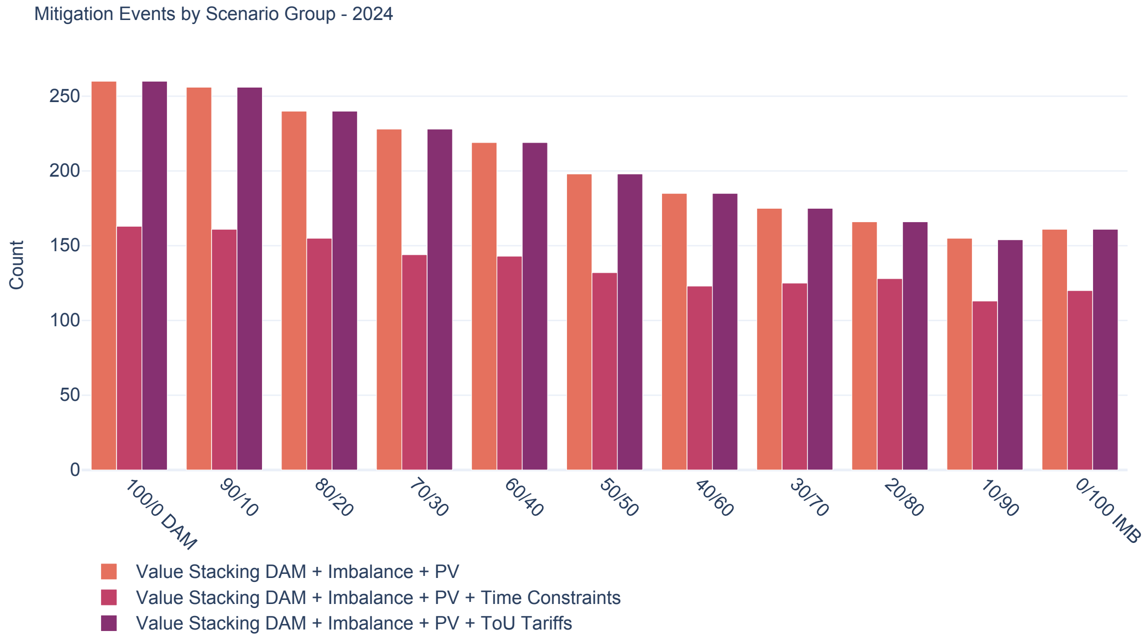

Figure F.12: Impact of market strategy and congestion-neutral constraints on mitigation of congestion in 2024.

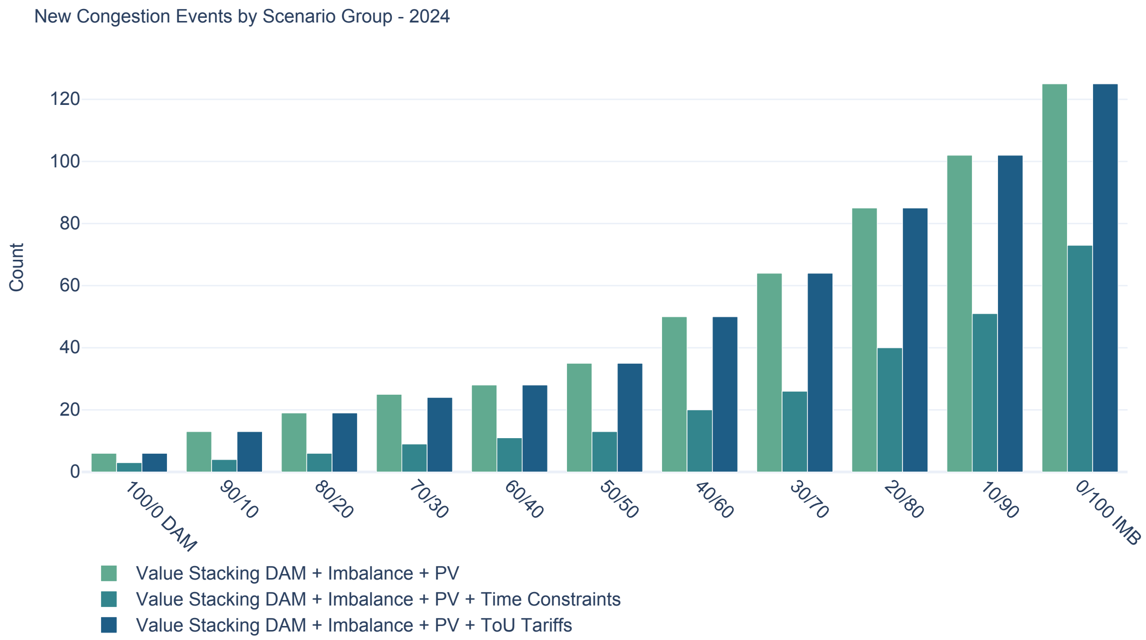

Figure F.13: : Impact of market strategy and congestion-neutral constraints on new congestion events in 2024.

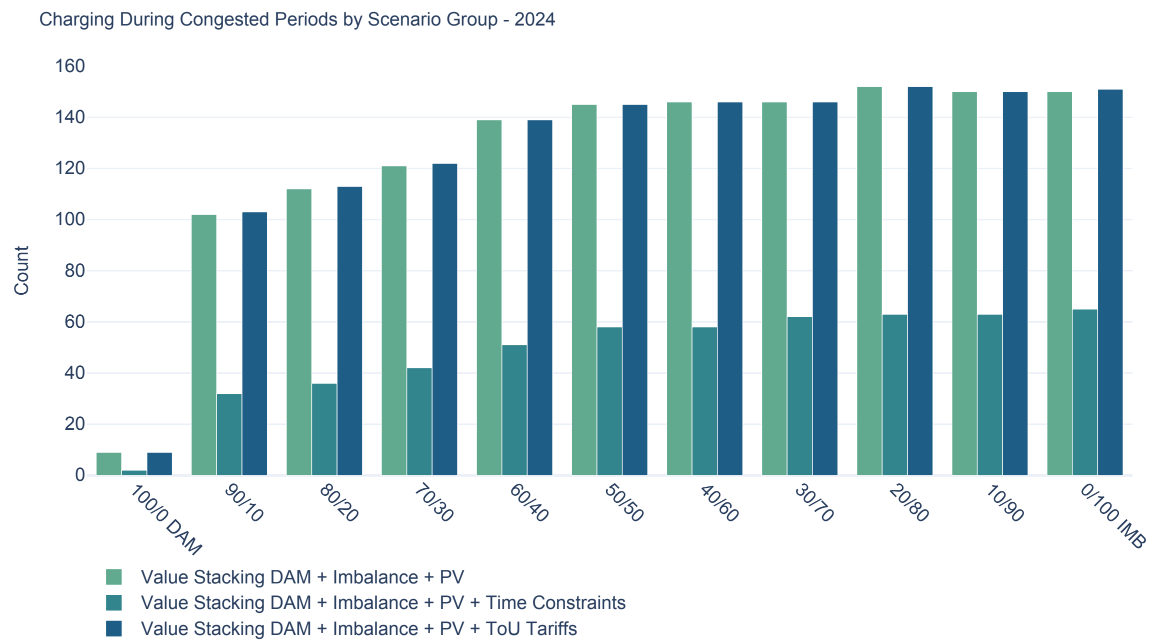

Figure F.14: Impact of market strategy and congestion-neutral constraints on charging during already congested periods in 2024.

F.5.1. 2030

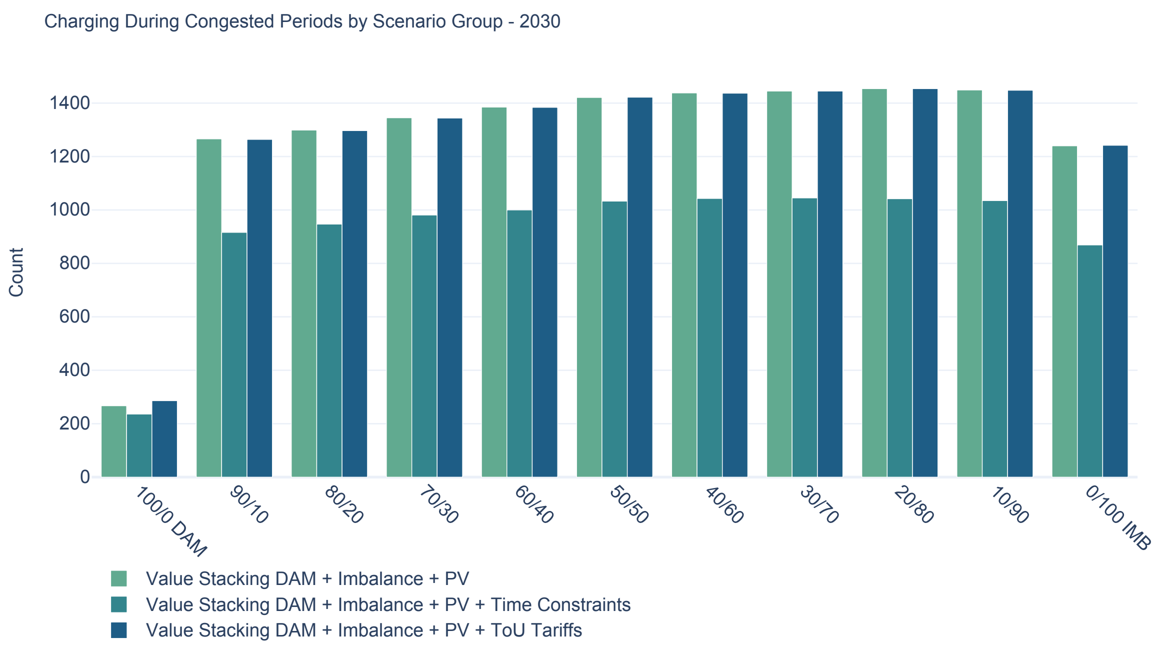

Figure F.15: Impact of market strategy and congestion-neutral constraints on charging during already congested periods in 2030.

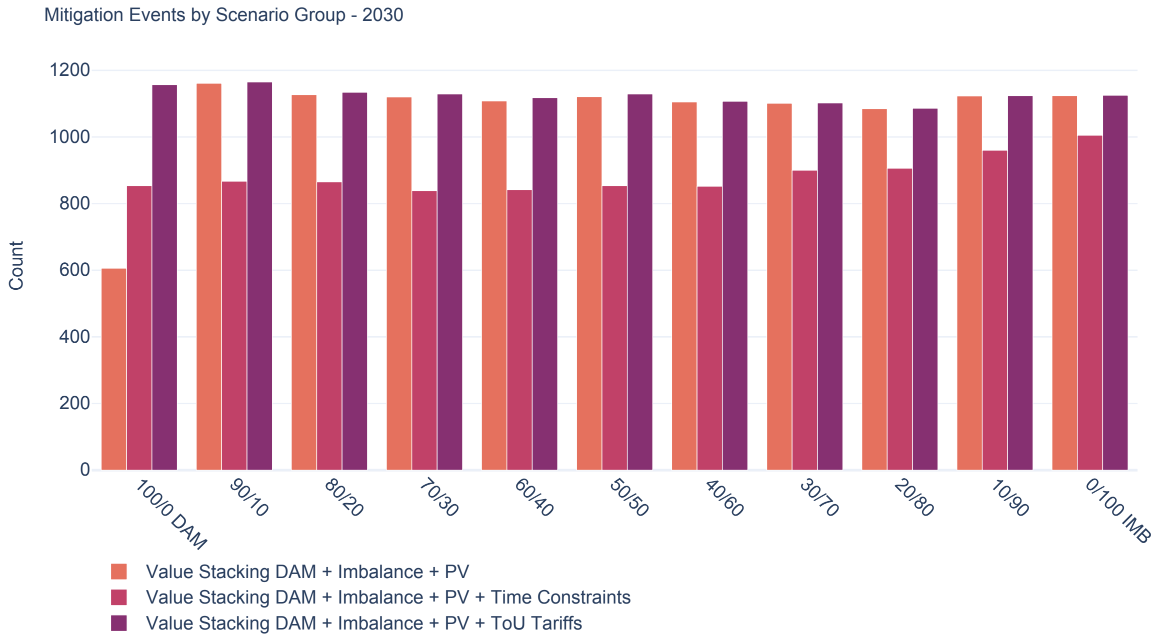

Figure F.16: : Impact of market strategy and congestion-neutral constraints on mitigation of congestion in 2030.

F.6. Heatmaps 2030

This appendix examines the time-specific behavior of R-BESS under value-stacking scenarios projected for 2030. Figure F.17 displays the intervals when charging overlaps with existing network congestion. Evening congestion peaks remain prominent for the imbalance market, but as imbalance trading increases, they extend more widely into daytime hours.

Figure F.18 identifies new congestion events triggered by battery charging. In contrast to 2024, when such events were largely centered around morning and evening peaks, the combination of an increase in already congested periods and less predictable imbalance signals produces additional congestion around noon in 2030.

Figure F.19 illustrates the moments when battery discharge relieves network stress. The primary mitigation window continues to align with the late afternoon. Together, these three heatmaps offer a detailed overview of exactly when battery flexibility either increases or decreases grid stress under each trading ratios.

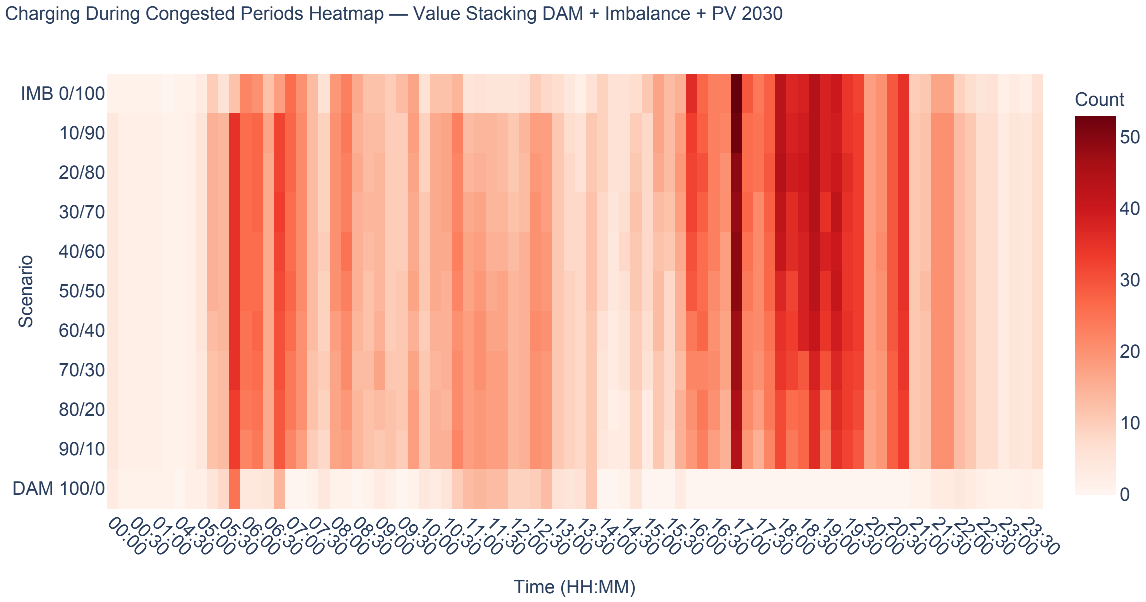

Figure F.17: Time-specific distribution of charging during already congested periods across different market participation ratios in 2030.

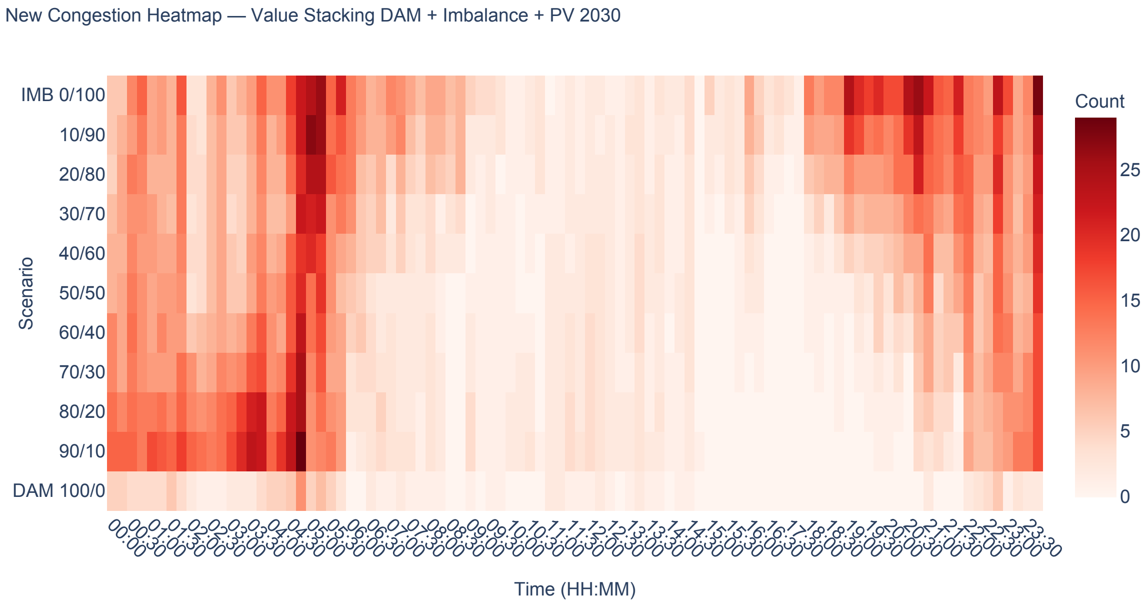

Figure F.18: Time-specific distribution of new congestion events caused by battery charging across different market participation ratios in 2030.

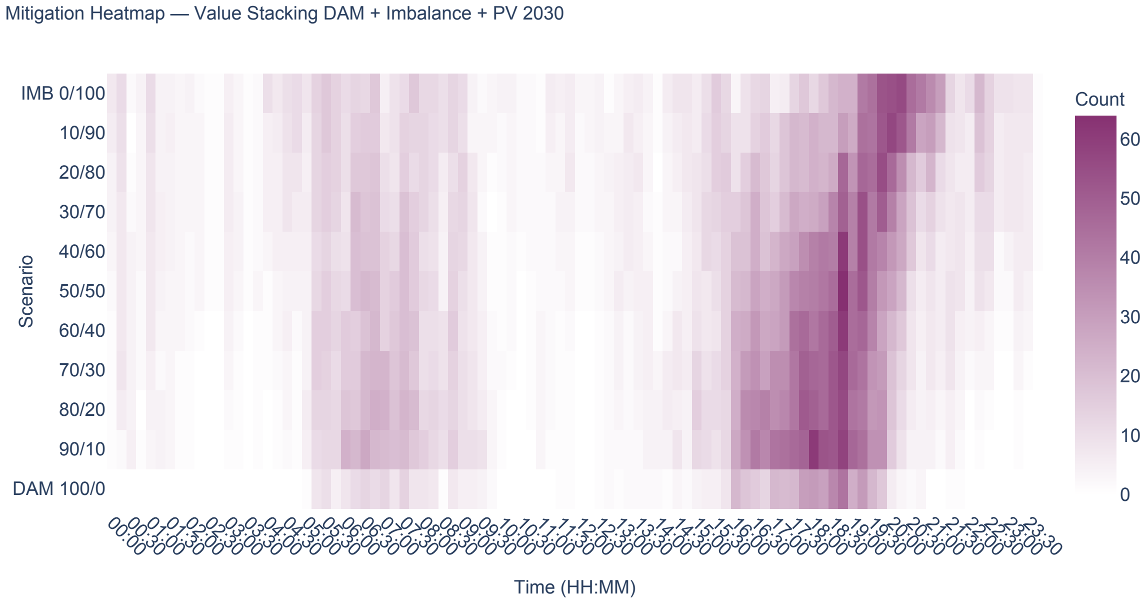

Figure F.19: Time-specific distribution of congestion mitigation events through battery discharging across different market participation ratios in 2030.

F.7. Charge and Discharge Behavior

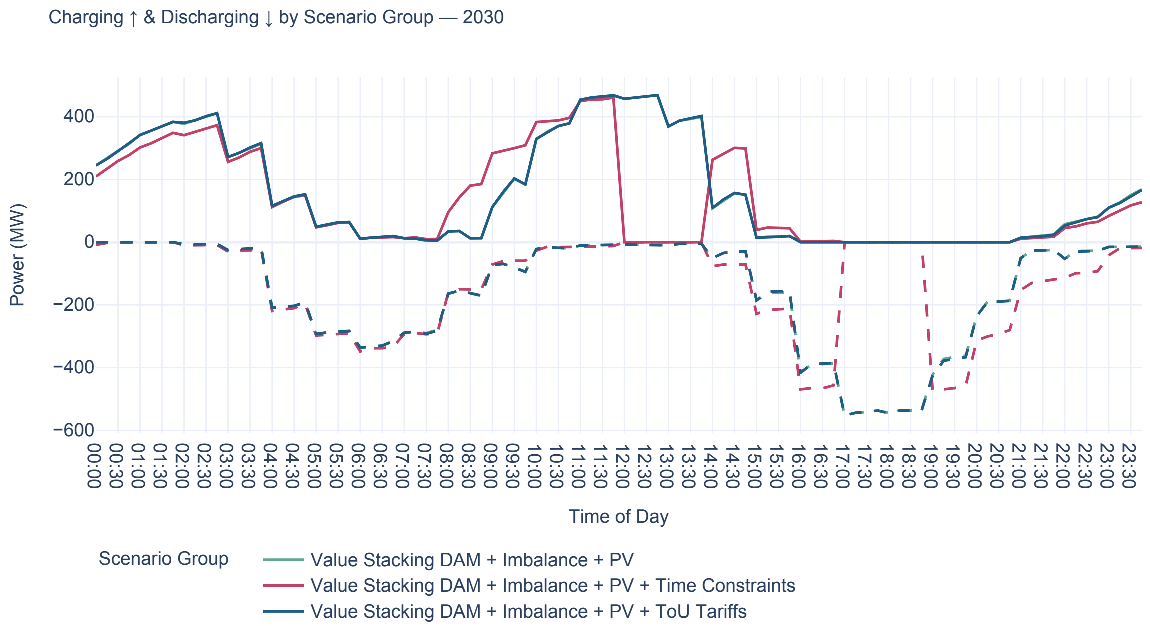

Figure F.20: Effect of congestion-neutral strategies on day-ahead battery charging and discharging profiles in 2030.

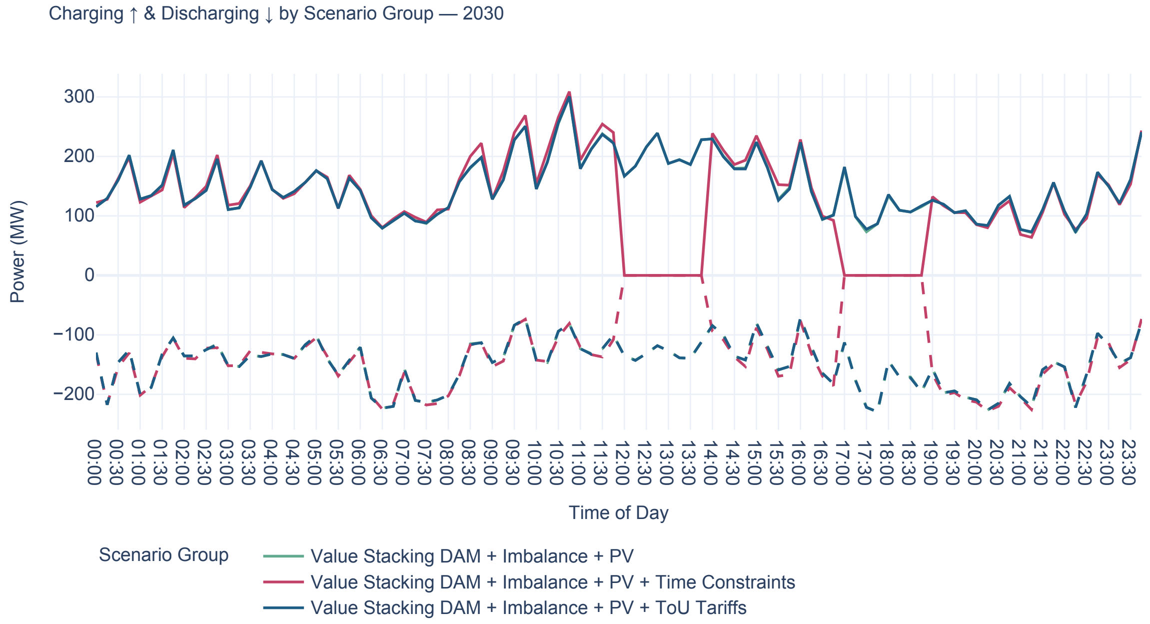

Figure F.21: Effect of congestion-neutral strategies on imbalance market battery charging and discharging profiles in 2030.

F.8. Objective Function

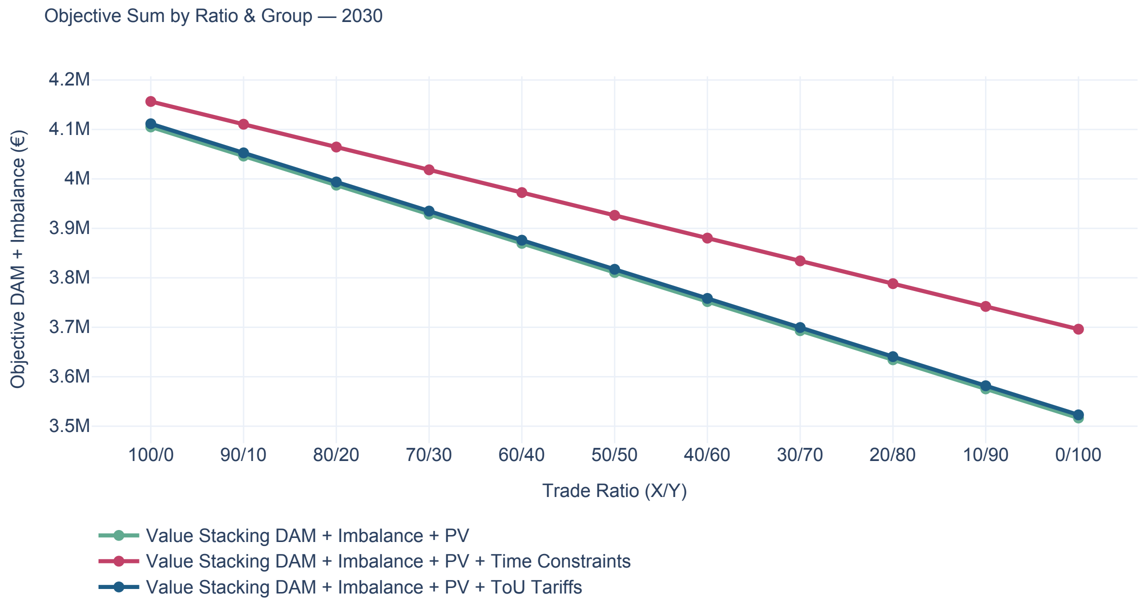

Figure F.22: Total system costs under different market participation ratios and congestion-neutral strategies in 2030.

F.9. Sensitivity Analysis

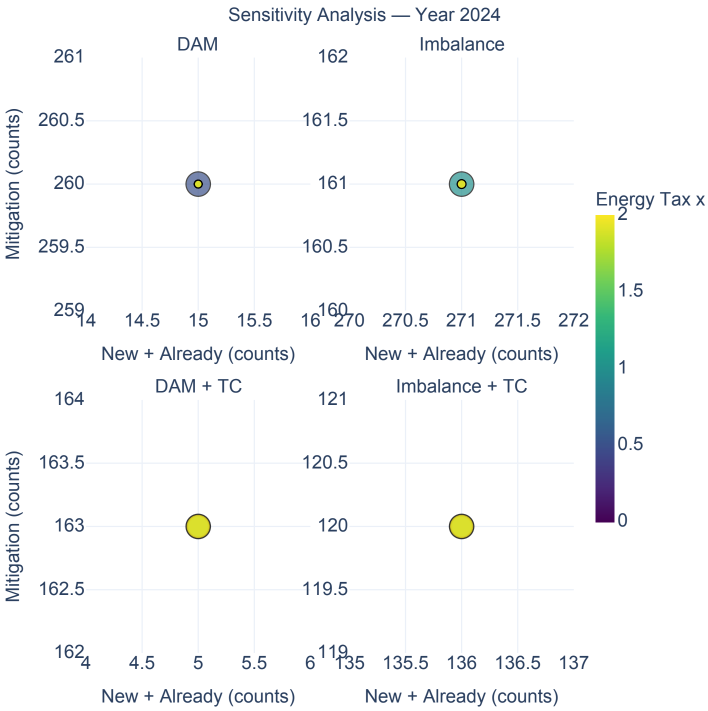

Figure F.23: Impact of an increase or decrease in energy tax on the ratio of new congestion and charging during already congested periods to mitigation events. The bubble size represents the total system costs, with a larger bubble visualizing higher costs.