Construction of a tariff model for Slim Strandnet

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Creating a tariff model for a decentralized microgrid

A case study for the Slim Strandnet project in Scheveningen

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Preface

This thesis marks the conclusion of my academic journey at TU Delft. It has been a process filled with both professional growth and personal development, and I am incredibly grateful for the many people who have helped me along the way. Throughout this period, I've encountered challenges that have shaped my understanding of not only complex energy systems, but also of myself as a researcher. I've learned to continue when the path ahead was unclear, to ask the right questions when answers were lacking, and to trust in the process, even when things didn't go as planned.

There were moments during this thesis when I found myself stuck, unable to see the bigger picture of my research. In those moments, I am especially thankful for the support of my supervisor and chair of the board, Dr. ir. Kenneth Bruninx. Kenneth always managed to bring clarity to complex issues, and his advice helped me find direction when I most needed it. I am particularly grateful for the backbone he provided for the operational energy model used in this research, which became an essential pillar of this thesis. I have learned an awful lot from Kenneth, and I truly cannot thank him enough.

My second supervisor, Dr. Simon Tindemans, was also an incredibly valuable part of my graduation board. Whether during the kick-off, mid-term, or green-light meetings, Simon's deep knowledge of the problem space and sector always brought thoughtful insights and meaningful questions. His presence and contributions were always very welcome, and I am grateful to have had him involved in this project.

I also want to thank Dr. Patrick Segeren, my supervisor from the Slim Strandnet project team. Patrick was always available to discuss anything related to the project, technical, conceptual, economical or strategic, and this open collaboration made me truly invested in the success of Slim Strandnet. His enthusiasm and engagement inspired me to give my best and to see this project not only as a thesis but as a meaningful contribution.

With sincere gratitude, I hope you enjoy reading this thesis.

Geert Marijn Helleman

5871794

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Summary

This thesis investigates how a hybrid tariff model can be designed and implemented to support financially sustainable, transparent, and operationally efficient energy usage in decentralized smart grids, using the Slim Strandnet microgrid in Scheveningen as a real-world case study. As decentralized energy systems gain prominence in the energy transition, conventional tariff structures, designed for centralized, uni-directional energy flows, fall short in capturing the complexity and potential of these new configurations. This research addresses this gap by proposing and evaluating a novel tariff framework that distinguishes between energy-related and grid-related costs, and allocates them using a combination of dynamic pricing and cooperative cost-sharing mechanisms.

The central research question guiding this study is: How can a tariff model be developed for a local smart grid such as Slim Strandnet that incentivizes efficient use of the grid connection and distributes costs and benefits based on each participant's contribution to balancing locally generated energy supply and demand? This overarching question is explored through three sub-questions focused on (1) the operational and financial benefits of collaboration in energy communities, (2) the applicability of cost allocation and pricing methods from the scientific literature, and (3) strategies to ensure financial risk mitigation for less flexible participants.

The thesis employs a dual-model approach. First, an operational energy model, based on agent-based decentralized optimization (ADMM), simulates energy flows and flexibility asset usage within the community. Second, a hybrid tariff model combines dynamic pricing for energy costs with ex-post allocation using Keys of Repartition (KoR) for grid-related costs. This layered structure allows the model to provide real-time behavioural incentives while ensuring fairness in cost and benefit allocation.

The Slim Strandnet case study includes eight simulation scenarios across three representative months (October, December, March), evaluating different combinations of tariff types and contractual arrangements such as Group Transport Agreements (GTA). The results demonstrate that collaborative operation significantly reduces peak demand and contracted grid capacity, leading to cost savings of up to 30%. Moreover, the hybrid RTP–KoR model effectively captures and redistributes flexibility benefits, with the KoR mechanism allocating shared costs in proportion to measurable contributions like peak load reduction and battery use. However, the findings also highlight that while RTP enhances system efficiency, it introduces price volatility that can disadvantage inflexible users.

To address this, the thesis proposes and evaluates financial protection mechanisms such as collective billing, community reserve funds, and flexibility credit schemes. These tools, although not yet implemented in practice, are shown to be compatible with the existing Slim Strandnet framework and supported by literature.

In conclusion, this thesis offers a scientifically grounded and practically tested tariff design that aligns operational incentives with fairness and financial security. It contributes both a methodological blueprint and empirical validation for future decentralized energy communities, demonstrating how collaborative tariff models can enhance the sustainability and resilience of local energy systems.

Nomenclature

Abbreviations

Abbreviation	Definition
ADMM	Alternating Direction Method of Multipliers
BESS	Battery energy storage systems
CoSEM	Complex Systems Engineering and Management
DR	Demand response
DSO	Distribution System Operator
EV	Electric Vehicle
GTA	group transport agreement
KoR	Keys of Repartition
kW contract	Contracted Grid Capacity
kW max	Maximum Grid Load (measured peak capacity)
LEC	Local Energy Community
PV	Photovoltaic
RTP	Real-Time Pricing
ToU	Time-of-Use Pricing
EMS	Energy Management System

Symbols

Symbol	Definition
t	Index of discrete timesteps within the simulation horizon
T	Set of all timesteps
g(t)	Net energy exchanged by an agent at time *t*
λ(t)	Internal electricity price at time *t*
D(t)	Electricity demand of a consumer at time *t*
AC(t)	Available generation capacity of a generator at time *t*
B(t)	Time-varying linear cost of generation at time *t*
c(t)	Energy charged into a battery or EV at time *t*
d(t)	Energy discharged from a battery or EV at time *t*
d_ev(t)	Energy transferred into an EV battery (leaves the system) at time *t*
SOC(t)	State of charge (battery or EV) at time *t*
SOC_max	Maximum storage capacity
C_max	Maximum charging power
D_max	Maximum discharging power
D_ev_max	Maximum power discharged into the EV battery
η	Round-trip efficiency factor (charge/discharge efficiency)
loss_hp	Standby thermal loss rate per timestep for the heat pump
c_hp(t)	Electricity consumed by the heat pump at time *t*
SOC_hp(t)	Thermal energy stored in the heat pump at time *t*
g_import(t)	Electricity imported from the national grid at time *t*
g_export(t)	Electricity exported to the national grid at time *t*
gnett(t)	Net grid exchange: gnett(t) = g_import(t) − g_export(t)
Import_B(t)	Price for importing electricity from the grid at time *t*
Export_B(t)	Price received for exporting electricity to the grid at time *t*
GridCapacity(t)	Maximum allowed import/export at time *t*

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1. Introduction

1.1 Context

The global energy landscape is undergoing a rapid transformation, driven by increasing electrification and a global shift from fossil fuels to renewable energy sources. The International Energy Agency (IEA, 2024) predicts that global electricity demand will rise by 3.4% annually until 2026, intensifying existing challenges in grid stability and energy distribution. In the Netherlands, however, these global trends have distinct local implications. National forecasts indicate that while overall energy demand may only marginally increase, between 2020 and 2050, the proportion of electricity in the total energy mix is expected to rise significantly. In fact, the proportion of electricity within the overall energy demand in the Netherlands is accordingly projected to rise from less than 20% in 2020 to over 40%, and potentially to approximately 60% by 2050 (Planbureau voor de leefomgeving, 2024). This shift is driven by a widespread adoption of renewable energy technologies, whether being generational technologies such as solar panels, or flexible assets as heat pumps and electric vehicle charging stations (Rijksoverheid, n.d.). This shift is intensifying challenges related to grid stability and congestion within the Netherlands. Thus, without serious changes to the way the grid is designed and operated, it may become a barrier against the transition towards a sustainable society (Bollen, 2011).

To address these issues, increasing attention is being given to the development of smart grids, which are intelligent electricity networks that leverage digital technologies to optimize energy generation, distribution, and consumption (Escobar et al., 2021). Smart grids can dynamically respond to fluctuations in both energy demand and generation of renewable energy sources, which is essential for supporting the continued growth of the share of sustainable energy and helps with mitigating network congestion (Zonneplan, n.d.). However, a key challenge within local smart grids lies in the implementation of a coherent tariff system that ensures cost recovery while equitably distributing the external costs and benefits among the participants of the smart grid. A suitable tariff system is essential for the effective operation of the smart grid and for encouraging sustainable energy behaviour. This is achieved by promoting demand shifting during periods of high demand or low supply, thereby reducing stress on the grid. Given the underexplored nature, this research focuses on developing a tariff model for the Slim Strandnet project in Scheveningen, The Hague. This Slim Strandnet project is an innovative initiative demonstrating how local collaboration, supported by smart technologies, as flex-assets and solar pv, can enhance energy independence and overall grid resilience, even as the smart-grid remains connected to the larger Dutch grid.

1.2 Slim Strandnet

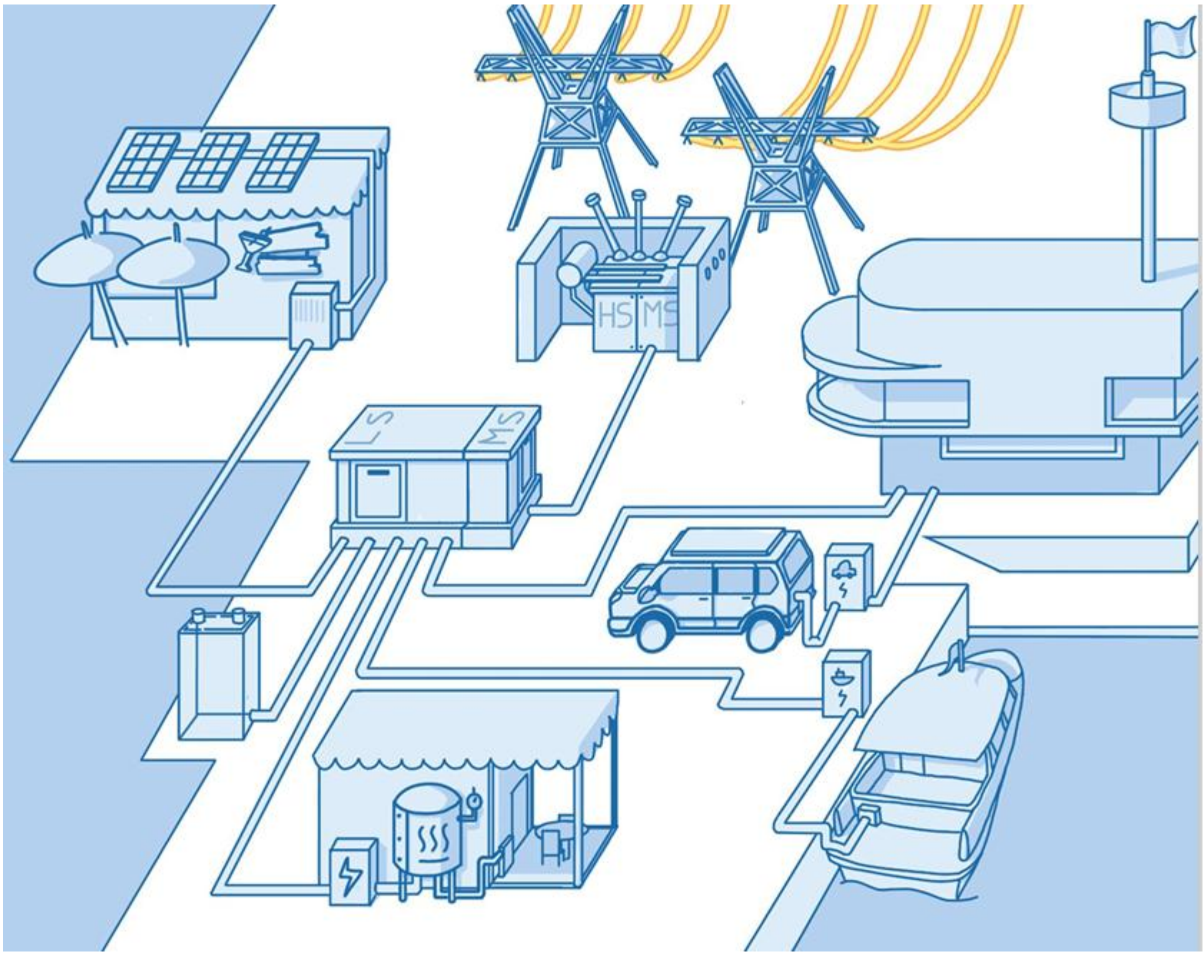


Figure 1: Schematic overview of the Slim Strandnet project

The Slim Strandnet microgrid, as schematically visualized in Figure 1 above, is a decentralized microgrid located in Scheveningen, The Hague. This microgrid has been developed by the Municipality of The Hague in collaboration with Dutch distribution system operator (DSO) Stedin and local businesses. The project serves as a key initiative within the broader Living Lab Scheveningen smart city program (Gemeente Den Haag, 2024). This microgrid is physically continuously connected to the national electricity grid, but it operates semi-autonomously through the integration of advanced digital infrastructure and flex assets.

The Slim Strandnet microgrid includes a heterogeneous mix of participants, consisting of local electricity consumers such as a marine control center, a working spot and several beachfront pavilions. The supply of electricity stems from both partly a connection to the Dutch national grid and partly by local renewable generation in the form of a solar park and rooftop photovoltaic (PV) systems. The electricity usage of the participants is continuously monitored and managed through smart metering, enabling the system to work with more dynamic pricing schemes. Additionally, shared flexible assets such as battery energy storage systems, heat pumps and electric vehicle (EV) charging infrastructure are incorporated into the grid to balance supply and demand dynamically.

The system's smart EMS enables real-time data exchange between energy consumers, producers, and storage units, allowing for coordinated energy use and load balancing. This reduces reliance on the main grid during peak periods. By leveraging localized generation and flexibility, the Slim Strandnet exemplifies how smart microgrids can contribute to both grid stability and the broader goals of the energy transition.

1.3 Literature gap and scientific contribution

While recent literature has advanced the fields of dynamic electricity pricing and ex-post cost allocation, it rarely integrates these components into a unified framework tested with real-world data stemming from an existing smart grid such as Slim Strandnet. Studies like Mustika et al. (2022) and Putratama et al. (2023) provide foundational approaches by respectively proposing two-stage and three-stage strategies that combine energy management with settlement mechanisms. However, there is little literature that explicitly distinguishes between energy-related costs and grid-related costs within decentralized tariff models. Most approaches treat these costs homogeneously, overlooking the operational nuances and allocation challenges introduced when local flexibility assets are shared across diverse consumer types. This thesis addresses that gap by explicitly separating these two cost domains and applying dedicated allocation mechanisms tailored to each.

In addition, while Mustika et al. (2022) conceptually explore the integration of price signals and fairness mechanisms through Keys of Repartition (KoR), and Putratama et al. (2023) include dynamic coordination under grid constraints, the use of embedded financial protection strategies remains underexplored in practice. By simulating high-volatility pricing scenarios within a functioning smart grid community, this research highlights the operational value of embedding such financial safeguards into the tariff design. In conclusion, this study contributes to academic discourse by operationalizing a hybrid RTP–KoR tariff structure in a real-world pilot, and by demonstrating how technical coordination and equitable cost distribution can co-exist within decentralized, smart grid environments.

While recent literature has advanced the fields of dynamic electricity pricing and ex-post cost allocation, it rarely integrates these components into a unified framework tested with real-world data stemming from an existing smart grid (Slim Strandnet). Moreover, there is little literature working with a distinction between energy-related costs and grid-related costs, within the context of decentralized energy grids. This thesis addresses this gap by explicitly separating these cost domains and applying dedicated allocation mechanisms. By simulating different scenarios, including high cost volatility, the research highlights the importance of embedded price-stabilizing mechanisms such as a combination of collective billing and community reserves, tools that have been conceptually proposed but rarely examined in practice. In conclusion, the study contributes to academic discourse by operationalizing this hybrid tariff structure within the Slim Strandnet pilot.

1.4 Research Questions

The primary objective of this thesis is to develop a tariff model for the Slim Strandnet microgrid that allocates costs and benefits in a fair and transparent manner, while promoting sustainable energy usage through pricing incentives. Addressing identified literature gaps and informed by both theoretical and empirical studies on pricing mechanisms and cost-allocation methods, this research adopts an integrated approach combining mathematical modelling with an extensive literature review. The research is guided by the following research questions:

Main Research Question

How can a tariff model be developed for a local smart grid such as 'Slim Strandnet' that incentivizes efficient use of the grid connection and distributes costs and benefits based on each participant's contribution to balancing locally generated energy supply and demand?

To guide the main research-question, the study explores the following sub-questions:

Sub-Research Questions

1. *What are the potential financial and operational benefits of collaboration within a local energy community compared to individual energy contracts for both energy and grid related costs?*

This sub-question aims to investigate the financial and operational advantages of cooperative energy management, thereby justifying the collective approach inherent in Slim Strandnet.

2. *What existing methods for cost allocation and price setting within the scientific literature are applicable to local smart grids like the 'Slim Strandnet'?*

This sub-question seeks to review current literature on cost allocation mechanisms and pricing models, assessing their strengths and limitations, and determining their relevance for reallocating benefits among participants in Slim Strandnet.

3. *What alternative factors should be considered in designing a tariff model that provides financial security for the participants of the Slim Strandnet?*

In addressing this question, the research will analyse the multidimensional criteria, beyond mere operational efficiency, required for a tariff model to be socially acceptable and equitable for all participants.

Together, these research questions provide a structured guideline for the thesis towards developing a tariff model for local smart grids. The integrated approach contributes to the academic knowledge on dynamic pricing and cost allocation in the specific context of a local smart grid.

1.5 Slim Strandnet Scope & Limitations

The Slim Strandnet serves as the empirical use case, offering a realistic setting in which to simulate the technical and economic operation and the effects of a tariff model. The scope of this thesis consists of two parts, consisting of two different models. First, one that serves the main purpose of this thesis (Tariff model) and another one that contributes to the creation and testing of the former (Energy model), which will be elaborated on in chapter 2. Moreover, with the construction of the tariff model this thesis focusses on two different microgrid related cost streams, namely, energy related costs and grid related costs, a more thorough explanation of these two cost categories will follow in chapter 2.

While this thesis focuses specifically on the Slim Strandnet microgrid, one of the broader goals is to develop a methodological blueprint for similar decentralized energy systems. The approach, combining literature review, mathematical modelling, and simulation, is applied within the confined setting of a small-scale, distributed smart grid. As such, the results are relevant to local energy communities and cooperative grid initiatives, rather than to large-scale wholesale markets. This focus strengthens their applicability to real-world community microgrids.

1.6 Research Approach

This thesis employs a structured, interdisciplinary research approach to develop and evaluate a hybrid tariff model for decentralized smart grids, using the Slimme Strandnet as the primary use case. The research integrates both a literature review and two distinct modelling components: (1) an operational energy model that simulates the functioning of the Slimme Strandnet under various scenarios, and (2) a tariff model based on dynamic pricing and the ex-post cost and benefit allocation. The ultimate goal is to create a tariff framework that combines dynamic pricing with equitable post-settlement cost and benefit allocation, grounded in both academic theory and simulated usability for the Slimme Strandnet project, and potentially replicable for other decentralized energy communities.

Literature Review: The research begins with a comprehensive literature review conducted in two stages. First, a conceptual review introduces foundational concepts required to design both the operational and tariff models. The review establishes the importance of integrating behavioural incentives with transparency mechanisms, particularly in contexts where shared infrastructure and heterogeneous user profiles coexist (Mustika et al., 2022; Putratama et al., 2023). Second, a chapter is dedicated to the operationalization of the models, this chapter indicates the information needed to get the model operationalized.

Development of the Tariff Model: Building on the findings of the literature review, a hybrid tariff model is constructed that integrates dynamic pricing with ex-post cost and benefit allocation in a two-layered billing and allocation system. This framework aims to enhance both operational efficiency and distributive fairness by periodically redistributing shared costs and benefits based on users' measurable contributions.

Development of the Operational Energy Model: To simulate the actual operation of Slimme Strandnet, an agent-based operational model is developed. Consisting of independent agents with own objective function and constraints. These agents are interconnected through a global energy balance constraint, the functionality of this operational energy model is explained in detail in chapter 4.

Collective Benefits of Smart Grid Participation: This sub-question investigates the potential economic benefits of forming a local energy community versus maintaining individual grid contracts. Through scenario simulations, the model quantifies avoided volumes associated with peak demand (kW max) and contracted capacity (kW contract), key elements in the Dutch DSO tariff system. To reflect realistic potential, a Group Transport Agreement (GTA) is introduced as a simulated coordination mechanism, exploring its ability to reduce these cost components through collective peak management.

Fair Redistribution of Costs and Benefits: This sub-question evaluates how shared operational results can be fairly allocated among heterogeneous users. Using output from the operational model, KoR-based mechanisms are tested to distribute shared value using predefined mathematical rules. The fairness and behavioural impact of these strategies are compared against theoretical expectations.

Price Risk and Protection Mechanisms: The final sub-question investigates how tariff designs can shield participants from extreme price volatility under dynamic pricing. The model is used to simulate stress events, followed by qualitative evaluation of mitigation tools such as collective billing buffers or fixed-rate overlays. These tests reveal the need for a balance between market exposure and participant protection, especially for users with limited flexibility (Hupez, 2022; Schittekatte & Batlle, 2023).

Overall, this research approach provides a cohesive methodology to test, evaluate, and iterate upon hybrid tariff designs using realistic data and theory-based fairness principles in a real-world community energy context.

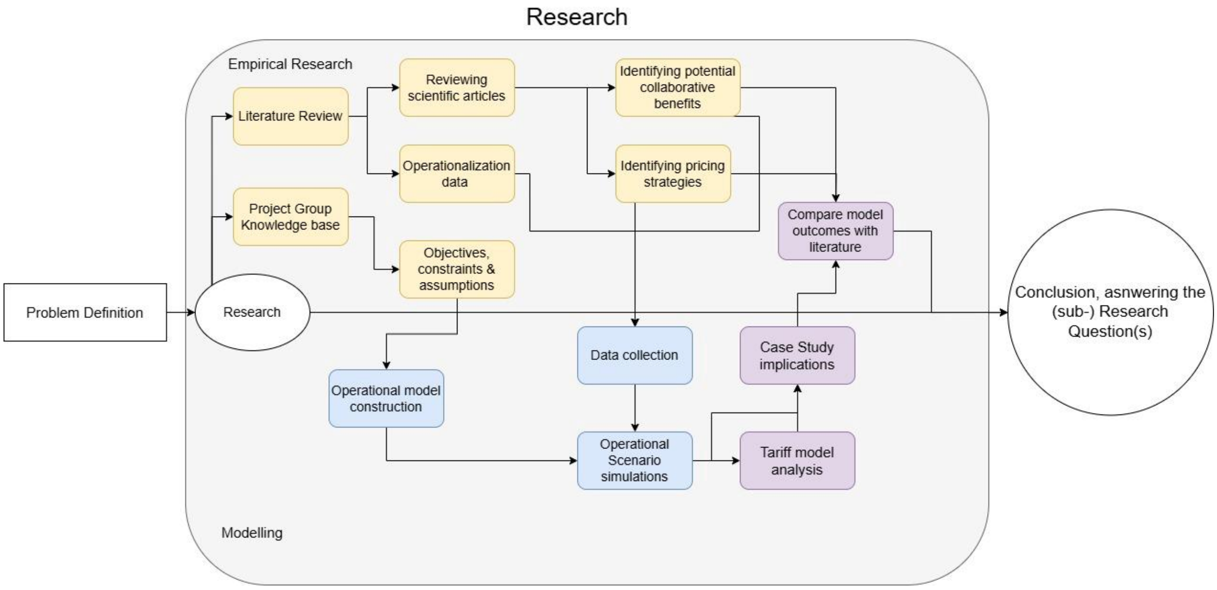


Figure 2: Research Flow Diagram indicating the research process

The figure above shows the research flow diagram, indicating that there is a clear distinction between two levels of the research, namely, the qualitative literature research on the upper half of the diagram and the quantitative modelling approach on the lower side of the diagram. Where the qualitative study is marked with the yellow colour, the quantitative modelling with the blue colour and a combination of the two mainly consisting of analysis is marked purple. The qualitative research forms the basis for the inputs of both the operational energy model and the hybrid tariff model in this research, this way this research is academically grounded. Finally the outcomes of the Slim Strandnet case study are discussed and compared to the literature and the conclusion provides answers to the sub questions together enabling the research to answer the main research question.

1.7 Link to CoSEM

My master's program in Complex Systems Engineering and Management (CoSEM) at the TU Delft, with a particular emphasis on the energy domain, focuses on the design and management of complex socio-technical system. The program takes an interdisciplinary approach, integrating technical, economic, and social perspectives to develop innovative solutions for a wide variety of challenges, especially within the energy sector. This research directly aligns with these objectives, as it addresses the complex interplay between technological feasibility, economic viability, and the creation of support and legitimacy for the participants of the project.

As well as, the inclusion of a thorough literature review combined with a modelling approach and a scenario analysis, this thesis combines a complete set of CoSEM ideologies and brings it to practice. My specialization in the energy domain was particularly valuable in enabling a strong understanding of market structures, participant incentives, and regulatory frameworks. Moreover, this works both ways around of course, as this project has brought me a lot of relevant industry knowledge in a more practical manner. By actually joining the discussion table with a group of stakeholders and actively discussing the possibilities and obstacles of the project the socio-technical aspects of CoSEM have been tested and improved continuously.

1.9 Thesis Outline

Chapter 2 – Literature Review Presents existing academic literature on smart grids, decentralized energy communities. It identifies key theoretical frameworks and highlights knowledge gaps addressed in this study.

Chapter 3 – Operationalization of the models Presents all information needed to operationalize both models used in this research.

Chapter 4 – Methodology Describes the research design, including data sources, model formulation, simulation setup and validation procedures. The Slim Strandnet is introduced as a real-world use case to test the hybrid model under practical conditions.

Chapter 5 – Use Case Slim Strandnet The Slim Strandnet is used as a use case to present specific and detailed results and scenario analysis.

Chapter 6 – Discussion Presents the process of this research as well as the implications, limitations and future research. And discusses potential interesting topics regarding this subject.

Chapter 7 – Conclusion and Recommendations Summarizes the key findings, reflects on the implications for decentralized energy policy and tariff design, and suggests directions for future research and real-world application of the proposed model.

2 Literature review

This literature review chapter systematically examines the key concepts and methodologies essential for creating context and providing a state of the art overview of existing scientific literature. The review is organized into distinct sections that first clarify core concepts relevant to (local) decentralized energy communities, next there is a section with literature regarding pricing and cost allocation methods, followed by literature regarding energy modelling. The chapter concludes by highlighting literature gaps and outlining the scientific contributions of this research, thereby providing a comprehensive theoretical foundation that underpins the development of an equitable and dynamic tariff model for local smart grids.

2.1 Local energy communities

The focus of this research is based around tariff models for smart grids, with the Slim Strandnet project being the main point of focus. Smart grids offer numerous advantages, particularly in terms of flexibility and renewable energy integration. First of all, smart grids are intelligent electricity networks that leverage digital technologies to optimize energy generation, distribution, and consumption (Escobar et al., 2021). Moreover, key benefits frequently highlighted in the literature are cost reduction and efficiency gains. In addition, shared energy storage and collective infrastructure can significantly lower operational expenses, as demonstrated by Pei et al. (2024), showing that shared energy storage enhances flexibility while reducing costs.

Moreover, next to offering economic benefits, smart grids also play a crucial role in maximizing the use of renewable energy sources, which is a key target of the Slim Strandnet project. Faerber et al. (2018) argue that decentralized energy generation reduces dependence on the central grid while enhancing overall energy system stability. Eid et al. (2016) and Barabino et al. (2020) demonstrate that demand response strategies and dynamic pricing incentives positively influence the integration of renewable energy. In addition to economic and environmental advantages, smart grids also have positive operational benefits by increasing grid flexibility and stability. Pei et al. (2024) and Barabino et al. (2020) show that smart energy storage mitigates fluctuations in supply and demand, contributing to a more stable energy supply.

However, effective demand management within smart-grids remains a challenge. Whereas, traditional demand response approaches are functionally insufficient in decentralized settings, where energy consumption is highly heterogeneous and influenced by localized factors. As a result, local smart grids require the integration of smart demand management strategies that can dynamically respond to rapid shifts in energy use. The success of models capable of this hinges on accurately capturing local consumption behaviours and deploying reliable communication networks to support responsive pricing adjustments (Srinivasan et al., 2017; Tsao et al., 2024). In the Netherlands, projects like Slim Strandnet align with national energy transition targets, as outlined in the Klimaatakkoord, which emphasizes flexibility, consumer empowerment, and decentralization (Rijksoverheid, 2019). Slim Strandnet functions as a "living lab," enabling experimentation with advanced smart grid concepts in a real-world setting through the cooperation of the Municipality of The Hague, DSO Stedin, and local partners. As such, it offers a unique context for testing different components of a new to be designed tariff model such as dynamic pricing strategies, flexible infrastructure deployment, and fair cost allocation within decentralized systems.

2.2 Challenges and drivers in local energy communities

The successful implementation of local decentralized energy communities and smart grids depends on overcoming a set of technical and behavioural challenges while leveraging key enablers such as flexibility. One of the leading technical barriers is maintaining grid stability in the presence of renewable energy generation. Moreover, to counterbalance these fluctuations, local grids must integrate demand-side flexibility and energy storage solutions. As highlighted by Zhang et al. (2021), energy communities that incorporate battery storage and flexible demand can effectively reduce peak loads and absorb excess renewable generation. Demand flexibility mechanisms do not only contribute to operational stability but also support economic optimization by allowing users to respond to dynamic pricing signals (Srinivasan et al., 2017; Parisio et al., 2015). Moreover, decentralized storage solutions, like a community battery, can be particularly effective in mitigating short-term volatility and reducing grid dependency during peak periods (Pei et al., 2024).

However, the adoption of such technologies and practices is often hindered by behavioural barriers. On the consumer side, limited awareness, risk aversion, and lack of knowledge can hinder active participation in flexible energy programs (Parag & Sovacool, 2016). Even when technical solutions are available, end-users may be unwilling or unable to engage in demand response schemes due to unflexible consumption patterns or concerns about ease and independency (Schittekatte & Meeus, 2020). Therefore, the construction and implementation of a tariff model that is able to provide the flexibility incentives in combination with a transparent and equitable cost and benefit distribution is needed to keep a high grade of reliability for the system and participants.

2.2.1 Potential collaborative benefits

A primary motivation for organizing consumers into decentralized energy communities, such as the Slim Strandnet, is to unlock operational and financial efficiencies in grid related costs unachievable through individual grid contracts. The Dutch distribution system operator (DSO) Stedin, directly involved with the Slim Strandnet project, applies a multi-component tariff structure for electricity transport costs, comprising the following five cost factors:

kWmax	Based on highest measured peak load
kWcontract	Fixed contractual agreement on capacity
Volume-based costs	Based on total energy transported
Transport fee	Base fees for grid connection
Connection charge	One-time fees for physical grid connection

Table 1: Overview of grid related costs

When consumers are connected individually, the cumulative effect of these factors can become disproportionately high, especially when looking at the kWmax and kWcontract part of the grid related costs. Operating as a collective allows for diversity effects, where not all users consume at their peak simultaneously, enabling a shared contractual peak that is considerably lower, this phenomenon is known as the coincidence factor. The coincidence factor is defined as the ratio of the system's peak demand to the sum of individual peak demands, indicating the likelihood of simultaneous peak usage among consumers (Michaels Energy, 2019).

Based on the above mentioned tariff components, two main regions for potential benefits emerge. First of all, kW max (measured peak), collective peak demand could turn out lower due to load diversity than cumulative individual peaks. Implementing battery storage and demand response strategies can further reduce peak loads. Second, kW contract (reserved capacity), indicates a potential for a collective reduction on the grid reserved capacity for the same reason as above, the coincidence factor. Whereas, due to the likelihood of diversity effects, a lower shared capacity can be contracted collectively, avoiding individual over-dimensioning (Claeys, 2021).

Moreover, scientific literature agrees with the indication of potential operational efficiencies resulting in collective benefits. Du et al. (2020) compared cooperative and non-cooperative microgrid models, demonstrating that collaborative approaches lead to a fairer distribution of costs and benefits while also improving operational efficiency. Similarly, Pei et al. (2024) and Putratama et al. (2023) emphasized that shared storage, coordinated flexibility, and collective demand response can lead to 30–40% cost reductions in grid-related expenses. Particularly, Putratama et al. (2023) highlighted how coordinated grid usage reduces both contract and real-time grid impact, leading to lower collective grid fees under cooperative circumstances. In the context of the Slim Strandnet project, these findings suggest that by leveraging the diversity of consumption patterns among community members, significant operational and with that financial benefits can be realized.

2.3 Slim Strandnet Tariff Model

2.3.1 Introduction on Slim Strandnet tariff model

Designing an effective and fair tariff model is a critical challenge in the context of decentralized smart grids such as the Slim Strandnet. As energy systems become more distributed, with increasing integration of local renewable generation, storage assets, and heterogeneous consumption profiles, traditional tariff structures, often designed for centralized, one-directional grids, fall short in promoting efficient, flexible, and equitable outcomes (Eid et al., 2016; Schittekatte & Meeus, 2020). In smart grid communities, tariff models must not only reflect real-time system conditions but also allocate shared infrastructure costs and collective benefits in a way that maintains user trust and engagement (Mustika et al., 2022).

2.3.2 Cost Allocation Methods

The allocation of costs in smart grids and energy communities represents a central challenge that significantly affects not only economic efficiency but also user participation and social acceptance. In decentralized energy systems, conventional top-down pricing mechanisms fall short in capturing the complexity of local energy exchanges, distributed flexibility, and shared infrastructure (Eid et al., 2016; Barabino et al., 2020). These systems require more nuanced and adaptive allocation methods that reflect the real-time contributions of individual participants and support cooperative behaviour within the community (Mustika et al., 2022). Without appropriate mechanisms, cost allocation risks becoming a barrier to adoption.

To address these challenges, this section of the literature review will dive deeper in the existing scientific literature, by proposing a variety of cost allocation mechanisms. These approaches differ based on cost type affected, energy or grid related costs, timing, active of reactive, and behavioural assumptions cooperative versus individual optimization. These characteristics are shown in table 1.

Method Type	Cost Type Affected	When Allocated	Behavioural Assumption
Dynamic Pricing	Energy costs	Before operation (active)	Individual optimization
Ex-Post Allocation	Grid costs	After operation (reactive)	Cooperative optimization

Table 2: Overview of Cost allocation methods

Table 2 above summarizes the key characteristics for two different pricing parts for tariff models. The tariff model for a decentralized smart-grid, such as the Slim Strandnet, should address two distinct cost streams:, namely, energy and grid-related costs. Dynamic pricing determines costs of energy consumed from or fed into the grid, whereas, ex-post allocation focuses on grid-related costs. Moreover, dynamic pricing methods are allocated in real-time and are therefore an active method. Whereas, ex-post allocation is allocated after operation and is therefore a reactive method. Furthermore, dynamic pricing assumes an individual optimization based on varying prices on time and load. In contrast, ex-post allocation assumes a mixed cooperative optimization where collective costs and benefits of the microgrid are redistributed either collective or individual. Both approaches will be discussed in order to analyse the suitability for the specific context of the Slim Strandnet project.

First, the energy cost related pricing options in the form of dynamic pricing mechanisms are discussed, followed by the grid costs related ex-post allocation methods. Dynamic Pricing Mechanisms**,** regulate cost allocation by directly influencing user behaviour through time-sensitive price signals. The most frequently mentioned dynamic pricing mechanisms in scientific literature are the following;

Real-Time Pricing (RTP): Reflects hourly market prices, usually related to operational market conditions and therefore day-ahead energy market prices. Main focus of real-time pricing mechanisms is to reflect market conditions, trying to balance supply and demand by including pricing incentives.

Time-of-Use (ToU): Divides the day into different timesteps each connected to a certain energy price, a common way is day and night pricing, usually related to more average national grid conditions. This mechanism lacks the active real-time demand steering component form the real-time pricing mechanism.

These mechanisms both enhance a certain degree of demand response, as demonstrated by Srinivasan et al. (2017) and Seok & Kim (2023), leading to more balanced load profiles and lower system costs. However, the degree to which both dynamic pricing mechanisms hold a relation with the market conditions is different. Whereas, real-time pricing enhances demand response by having more fluctuations of prices than time-of-use pricing does, and therefore, enhances a bigger stimulation of demand response. Whereas, both mechanisms require advanced metering infrastructure and real-time communication. Equity remains a concern, namely, Eid et al. (2016) caution that certain participants may be unable to shift usage as easily, resulting in disproportionate financial burden.

Next to this, Ex-Post Allocation Methods allocate costs and benefits after system operation, based on measured participation or contribution. Two of the most frequently mentioned ex-post allocation methods for decentralized energy communities are the following;

Keys of Repartition: An ex-post allocation method where participants are allocated either financial or physical components of the microgrid based on weight factors. These weight factors are determined based on mathematical formulations that are predefined, either by a market operator or by the community as a whole.

Rule-Based Sharing: Costs distributed proportionally to predefined metrics. This is a more static mechanism than the keys of repartition mechanism.

Ex-post allocation methods redistribute costs and benefits after system operation, based on observed measurements. These methods allow for a more granular and transparent assignment of financial responsibilities and rewards, reflecting real system usage rather than static assumptions. One widely studied ex-post approach is the Keys of Repartition (KoR), which applies predefined or dynamic weighting factors to allocate collective outcomes among participants, some of the most commonly used inputs are shared energy production, flexibility contributions, or battery revenues (Mustika et al., 2022; Putratama et al., 2023).

Approach	Fairness	Behavioural Steering
Dynamic Pricing	-	+
Ex-Post allocation	+	-

Table 3: Overview of the stronger and weaker points of different cost allocation methods

Table 3 above highlights per approach the strength of two important factors when designing a tariff model for a smart grid, namely, the fairness of the approach and the behavioural steering of the approach. The dynamic pricing component is strong on the behavioural steering as the active pricing fluctuations stimulate demand response in the real time. However, the dynamic pricing component is relatively weak for the fairness of the tariff model, as it can discriminate users that are less able to shift demand in the real-time. On the other hand, the ex-post allocation approach increases the fairness of the tariff model by calculating the energy usage and impact of the users afterwards during a certain timeframe. This way the user only pays for the individual impact of their energy usage on the grid. Whereas, the behavioural steering of the ex-post allocation is very low, being calculated afterwards the incentive of the individual user to shift load in real-time is lacking. Taking this into account, the next sections will discuss both components of a tariff model in more detail.

2.3.3 Dynamic Pricing

The tariff model developed for the Slim Strandnet project incorporates a behavioural steering component, enabled by the use of dynamic pricing mechanisms. These mechanisms are essential in modern electricity systems, as they encourage users to shift their energy consumption in response to price signals, thereby improving grid efficiency and easing pressure during periods of high demand.

Two primary dynamic pricing mechanisms are widely used: Time-of-Use (TOU) pricing and Real-Time Pricing (RTP), each with distinct characteristics and implications.

TOU pricing is based on pre-set tariffs that vary by time blocks, typically distinguishing between peak and off-peak hours. While easy to implement and understand, TOU is relatively static and may not reflect real-time grid conditions. As a result, it can misalign price signals with actual system needs (Hogan, 2014).

Real-Time Pricing varies continuously, typically on an hourly or sub-hourly basis, and reflects current or forecasted market conditions. RTP provides more accurate price signals that can strongly incentivize demand response. Zhao et al. (2021) show that RTP is capable of achieving substantial peak load reductions and cost savings. However, this mechanism may expose less flexible users to financial volatility due to high price spikes.

Day-Ahead Pricing Prices determined one day in advance through wholesale market mechanisms (EPEX). This is related to real-time pricing but holds only for the external market. It does not take into account any market conditions from within the smart grid. However, the day-ahead price is used to steer consumer behaviour and is the price paid per kWh in the final billing.

The three mentioned dynamic pricing mechanisms will be compared to each other on relative advantages and disadvantages in table 4 below.

Pricing Mechanism	**Advantages**	**Disadvantages**
Time-of-Use	- Easy to understand and implement	- Inefficient in responding to volatility - Can over- or under-incentivize users due to predefined energy prices
Real-Time Pricing	- Strong relation with market conditions and demand shifting incentives	- Exposes inflexible users to price peaks

Day-Ahead Pricing	– Transparent and verifiable for users	– Fixed one day in advance, not responsive to intra-day changes - Does not take into account smart grid market conditions

Table 4: Overview of the advantages and disadvantages of different pricing mechanisms

Table 4 presents a comparison of the two dynamic pricing strategies evaluated, Time-of-Use and Real-Time Pricing. While day-ahead electricity prices are not real-time in a strict sense, they are often classified as a dynamic pricing mechanism, since they fluctuate daily based on expected supply and demand. In non-smart grid environments, real-time pricing for consumers often refers to day-ahead prices. These prices are public, fixed one day in advance, and serve as both consumer-facing signals and the basis for billing.

In contrast, within a smart grid context like Slim Strandnet, real-time pricing takes on a more specific operational meaning. Here, RTP refers to internal price signals generated by the EMS in response to local grid conditions, not the external market prices. These internal RTP values are used to steer the behaviour of flexible assets, such as community batteries and EV chargers, while consumers still see and are billed according to day-ahead market prices.

In conclusion, while Real-Time Pricing offers a more effective mechanism for behavioural steering, its implementation within smart grids requires nuance. In the Slim Strandnet model, this is addressed through a layered approach: day-ahead pricing is used for consumer transparency and billing, while internal RTP coordinates asset-level flexibility in real-time. To balance behavioural incentives with billing fairness, a second layer of the hybrid model, the Keys of Repartition, is introduced to redistribute costs and benefits based on actual system impact.

2.3.4 Mitigating Financial Risk in Real-Time Pricing

As energy systems become increasingly decentralized, the issue of price volatility presents a growing challenge for end users. In environments that rely on dynamic electricity pricing, unpredictable price movements can create economic uncertainty, particularly for users with limited flexibility or price awareness (Borenstein, 2005; Faruqui & Sergici, 2010; Burger et al., 2019). These risks are further amplified in systems with high penetration of renewable generation, where supply volatility often translates into increased price variability (Zhou et al., 2022).

While Real-Time Pricing (RTP) offers strong incentives for demand-side responsiveness, it can also lead to financial exposure for inflexible users. However, in the context of the Slim Strandnet model, this risk does not arise from RTP directly. Instead, billing is based on day-ahead electricity prices, which users can view in advance. These prices are dynamic, changing daily based on market expectations, and can exhibit significant fluctuations in times of market stress. Thus, volatility exposure in this project stems from day-ahead market pricing, not the internal RTP signals used by the energy management system to control shared flexible assets such as the battery and EV chargers.

To reduce user risk under dynamic pricing conditions, various mitigation strategies have been proposed. One widely supported approach is the implementation of collective billing, in which a community is billed as a single aggregated unit, and internal cost allocations are handled according to agreed rules (Hupez, 2022; Schittekatte & Batlle, 2023). This method spreads financial risk across the community and reduces the chance of individual users being penalized for short-term inflexibility. In Slim Strandnet, this collective approach is reinforced by the KoR-based cost allocation, which accounts for participant impact and smooths out volatility in a fair and transparent manner.

More advanced risk mitigation mechanisms are explored in Weiller and Pollitt (2013), including the use of community reserve funds or insurance-style derivatives that protect against extreme market conditions. For example, communities may allocate a portion of collected payments into a shared risk fund, or use threshold-based call options that activate when average prices exceed a given ceiling. Although not yet widely implemented, these mechanisms are gaining traction in peer-to-peer and microgrid contexts (Long et al., 2018), and could complement the foundational protections offered by collective billing frameworks.

Following are the two dominant financial risk mitigating mechanisms for local energy communities highlighted in the literature, which are integrable when combined with collective billing.

1. Community-Based Insurance Reserve Fund: A portion of each participant's monthly bill is allocated to a reserve fund managed within the smart grid community. When prices exceed a certain internal threshold the fund is used to compensate them. This approach relies entirely on internal governance and collective agreement (Weiller & Pollitt, 2013; Long et al., 2018).

2. Flexibility Credits with Risk Buffering: Participants who are willing to offer flexibility earn credits over time. These credits can then be used to offset future high-cost periods, functioning as a decentralized "insurance-like" buffer. This model creates long-term incentives while providing self-earned price relief during extreme events (Zhou et al., 2022).

Within the context of local energy communities, such as Slim Strandnet, where operational autonomy and participant engagement are high, internal security mechanisms offer a promising path to mitigate the financial risks associated with energy price volatility. As observed by Hupez (2022), collective billing enables communities to combine energy costs and distribute them internally according to predefined rules, thereby protecting individuals from price spikes. However, by solely integrating collective billing no financial risks due to price volatility is being mitigated. Thus, the collective billing must be combined with an extra financial risk mitigating mechanism.

However, while theoretically robust, the implementation of external financial risk mitigating mechanisms such as a insurance reserve fund introduces practical challenges. These challenges include the need for a clearly defined framework to manage contributions, determine payout conditions during periods of price stress, and ensure fairness in distribution. Zhou et al. (2022) note that insurance-based mechanisms, particularly in decentralized systems, require high levels of trust and transparency to maintain legitimacy.

An alternative mechanism discussed is the flexibility credit system, in which users earn credits by providing demand-side flexibility. While this model aligns with incentive-based allocation frameworks (Zhang et al., 2021), it adds considerable administrative complexity and relies on accurate real-time tracking and verification of flexibility behaviours. In the context of Slim Strandnet, such complexity may outweigh the benefits. As noted in 2.3.3, this illustrates the need for an extra layer within the tariff model next to the dynamic pricing, in order to fairly distribute costs and benefits and prevent individual participants from exposure to price peaks. Therefore, an literature review on ex-post cost and benefit allocation will follow in the next section.

2.3.5 Ex-Post Cost and Benefit Allocation

The distribution of costs and benefits in decentralized energy communities presents a core challenge in achieving both economic viability and user equity. Traditional real-time or flat-rate pricing mechanisms often fail to capture the full complexity of local grid interactions, especially when communities share infrastructure, generation assets, and flexibility resources. In response, ex-post allocation methods have gained traction as tools that distribute costs and benefits after the fact (Putratama et al., 2023; Contreras-Ocaña et al., 2021). Ex-post allocation methods operate by collecting operational data over a defined period. These data points are then used to calculate operational results corresponding to financial responsibilities and rewards, ensuring that users pay according to their actual burden on the system and receive benefits matching their contributions. This mechanism is particularly relevant in settings where local generation, demand-side flexibility, and shared storage play a significant role in community energy dynamics.

Among the ex-post allocation approaches, rule-based sharing and Keys of Repartition are two frequently mentioned methods. Rule-based sharing typically involves predefined formulas based on straightforward metrics such as total energy consumption or installed capacity. This method is easy to implement and transparent, making it suitable for communities that prioritize simplicity and administrative ease. However, they may overlook key value-generating actions within the system, which can reduce behavioural incentives and perceived fairness among participants (Mustika et al., 2022).

In contrast to static or rule-based allocation approaches, Keys of Repartition (KoR) offer a more refined method for distributing shared grid-related costs and benefits within a decentralized energy system. Rather than relying solely on proportional energy consumption, KoR uses predefined mathematical weightings that reflect each participant's impact on overall system behaviour, especially regarding collective outcomes such as peak load reduction. This approach is particularly relevant for smart grid environments like Slim Strandnet, where participants are interconnected through shared infrastructure and benefit from collaborative peak shaving efforts.

KoR acts as an ex-post allocation mechanism, evaluating participants' contributions after real-time operations have taken place and assigning cost and benefit shares accordingly. This ensures a transparent and justifiable redistribution of savings or costs, based on each user's relative contribution to community-wide performance metrics such as reduced kWmax or optimized kWcontract. As a result, KoR supports both fairness and community alignment, attributes especially critical in mixed-user systems like Slim Strandnet, where traditional cost allocation methods would ineffectively capture the value created through collective behaviour.

State-of-the-art tariff design literature strongly supports the methodological choices applied in this thesis. Mustika et al. (2022) demonstrated a two-stage framework in which energy management optimization was followed by ex-post cost allocation using the Keys of

Repartition. Their results showed measurable improvements in both fairness and cost efficiency. In the context of Slim Strandnet, where users share a grid connection and benefit from load diversity and heterogeneous consumption patterns, KoR offers a structured and transparent approach to allocating collective grid-related costs and benefits. Rather than relying on simple proportional billing, KoR distributes costs based on participants' actual impact on system performance.

Moreover, combining KoR with dynamic pricing enables the development of a hybrid model that balances operational responsiveness with long-term equity. In this setup, day-ahead prices provide ex-ante signals to steer user behaviour and form the basis for billing, while internal Real-Time Pricing coordinates the operation of shared assets such as batteries and EV chargers. The KoR mechanism, applied ex-post, then allocates system costs and benefits based on observed contributions to the community's operational outcomes. This two-layered structure, supported by both Mustika et al. (2022) and Putratama et al. (2023), ensures that short-term incentives are aligned with fair, system-level cost recovery.

A full description of how this hybrid tariff model is designed and applied within Slim Strandnet follows in Section 2.3.6.

2.3.6 Hybrid method explained

As introduced earlier, the hybrid tariff model combines two complementary mechanisms to address the dual challenges of short-term efficiency and long-term transparency in decentralized energy systems. The core objective is to balance operational efficiency achieved through dynamic pricing mechanisms that incentivize real-time behavioural response and equitable cost and benefit (re-)distribution, realized via ex-post allocation based on participants' actual contributions to system performance. By combining these elements, the hybrid model responds not only to the technical demands of smart grid operation but also to the social and institutional requirements of transparency, acceptance, and participant trust.

What distinguishes the hybrid tariff model introduced in this research is not only its integration of real-time and ex-post mechanisms, but also its clear functional separation between energy-related and grid-related cost domains. An important notice to be made is that, within a decentralized smart grid such as Slim Strandnet, there is a meaningful distinction between external market prices and internal steering prices. In this framework, energy-related costs are ultimately determined ex-post, based on the volume of electricity consumed and the corresponding day-ahead market prices at which the community procures its energy externally.

However, to guide real-time operational behaviour, the model incorporates an internal price signal, derived from but not identical to the day-ahead price. This internal price, functioning as a form of Real-Time Pricing, functions as a coordination price within the smart-grid as response to local conditions. While participants observe day-ahead prices upfront, it is this internal RTP signal that actively steers flexible assets such as batteries and electric vehicle chargers, thereby promoting system-wide responsiveness.

It is important to note that these internal prices are not used for final billing. Instead, they serve exclusively as operational signals, ensuring that behaviour aligns with both market trends and local grid constraints. The final energy bill is calculated ex-post using actual consumption data and the external day-ahead market prices, thereby reflecting the real cost of energy provision. The two forms of Real-Time Pricing discussed in this research are shown in table below.

Form of Dynamic Pricing	Definition	Functionality
Day-ahead prices	External market prices, paid per kWh.	Used for the steering of consumer behaviour. Used as the basis for final energy billing, reflecting the actual cost of electricity procurement.
Internal RTP	Coordination prices within the smart-grid	Used to steer behaviour of flexible assets

Table 5: Overview of the two forms of Real-Time Pricing

In parallel, the second layer of the model addresses grid-related costs, which are also settled ex-post. These costs, including those related to contracted capacity, measured peak demand, and shared infrastructure usage, are allocated using the Keys of Repartition methodology. Rather than relying on static or volumetric shares, KoR distributes these costs among participants based on their observable impact on the community's operational results. This approach, as supported in the work of Putratama et al. (2023), enhances fairness and aligns with the operational realities of local energy communities.

By explicitly decoupling the domains of energy and grid cost allocation, and by differentiating between external and internal pricing layers, the hybrid model provides participants with corrective transparency and behavioural steering as can be seen in Table 6 below.

Approach	Corrective Transparency	Behavioural Steering
Dynamic Pricing	**-**	+
Ex-Post	+	-
Slim Strandnet Hybrid Tariff Model	+	+

Table 6: Overview of the stronger and weaker points of different cost allocation methods including the Slim Strandnet model

Table 6 above provides a simplified overview of how the hybrid tariff model integrates the strengths of dynamic pricing and ex-post allocation. While real-time pricing mechanisms offer effective behavioural steering, they often lack corrective transparency in cost distribution. The hybrid model addresses this by combining ex-ante dynamic pricing with an ex-post cost allocation (KoR), which ensures that actual billing reflects each participant's measured impact on grid and energy usage.

It is also important to highlight that, although the hybrid model is deployed within a decentralized energy community, both its core components are centrally designed and coordinated. This centralized governance ensures transparency, accountability, and consistency in rule application, while still enabling decentralized user responses based on individual behaviour and flexibility. This model of central coordination with decentralized execution aligns with the broader objectives of the Slim Strandnet project, where local engagement, smart infrastructure, and structured oversight are intended to coexist.

The following Section 2.3.7 will further explore how these pricing mechanisms are tested and evaluated within the operational context of the Slim Strandnet microgrid.

2.3.7 Energy modelling

The integration of decentralized energy communities requires analytical tools capable of capturing the operational complexity inherent to such systems. Energy modelling plays a crucial role in this context, providing a means to anticipate system behaviour before implementing new pricing mechanisms, operational constraints, or infrastructure designs (el Assri et al., 2021). The energy model developed in this research must replicate the operational dynamics of the Slim Strandnet microgrid and evaluate the impact of the proposed hybrid tariff structure. This section reviews relevant literature on energy modelling for decentralized and smart grid systems to establish the theoretical foundation for the selected approach. It situates the chosen method within current academic discourse and ensures its suitability for analysing the implications of a hybrid RTP–KoR tariff framework.

By representing dynamic interactions between energy consumers, producers, and storage systems, operational models offer insights into how different tariff structures influence user costs, system efficiency, and fairness in cost and benefit allocation (el Assri et al., 2021; Mustika et al., 2022). Energy models are also instrumental in quantifying the value of shared infrastructure by simulating their contribution to peak reduction and the integration of local renewable energy. These simulations reveal the collective operational and financial benefits that are often inaccessible under individual energy contracts, as shown in recent studies of smart grids (Pei et al., 2024). In this thesis, energy modelling serves as the analytical foundation to assess the hybrid tariff model by enabling controlled comparisons of pricing strategies, collective benefits, and financial risk, through scenario-based simulations.

Within the domain of decentralized energy systems, four primary modelling approaches are widely used: centralized optimization models, agent-based simulations, and both cooperative and non-cooperative game-theoretic frameworks. Each method presents unique trade-offs between precision, behavioural realism, and scalability, especially when applied to systems with multiple heterogeneous participants.

Centralized optimization models formulate the system as a single, integrated objective function, often subject to global constraints such as power balance, or grid capacity (Mohsenian-Rad et al., 2010). These models provide high precision and control, making them well-suited for centralized system operation. However, they require full knowledge of all agent behaviours, centralized decision-making, and synchronous optimization. As such, they are less suitable for decentralized or modular systems where agent autonomy is critical (Koirala et al., 2016).

Agent-based models simulate the behaviour of individual actors through predefined rules or probabilistic responses to system stimuli (Zhang et al., 2018). This allows for rich behavioural heterogeneity and emergent dynamics, which can be useful in understanding complex socio-technical interactions. However, these models often lack formal optimization logic and do not ensure economically rational outcomes, making them less appropriate for simulating cost-driven decisions such as those involved in tariff schemes or infrastructure investment (Ghorbani et al., 2020).

Game-theoretic models are grounded in microeconomic principles and explicitly model the decision-making logic of individual. These can be categorized into **cooperative and non-cooperative frameworks. Cooperative game theory models** focus on shared utility maximization and fair allocation of joint benefits or costs (Contreras & Wu, 1999). While these models provide strong fairness guarantees, they require a high degree of coordination and information sharing. **Non-cooperative game theory**, in contrast, assumes that each agent acts in a self-interested and economically rational manner, seeking to optimize individual outcomes given the actions of others. When agents are subject to a shared constraint the system can be solved as a Nash equilibrium using iterative coordination methods. This approach allows for modular and scalable model design, where agents can be added or removed without restructuring the entire system.

Model Type	Mathematical Structure	Strengths and Limitations
Centralized Optimization	Global objective with system-wide constraints	High control and precision, but lacks modularity
Agent-Based Simulation	Rule-based, often stochastic, no formal optimization	Captures behavioural nuance, but lacks optimization logic
Cooperative Game Theory	Joint utility maximization with full information and coordination	Ensures fairness in theory, but unrealistic coordination burden and low flexibility
Non-Cooperative Game Theory	Independent agent objectives coordinated via shared constraints	Balances decentralization with coordination; modular and scalable

Table 7: Overview of strengths and limitations of different energy models including the Slim Strandnet operational model

As shown in Table 7, each modelling approach presents trade-offs between precision, modularity, behavioural realism, and optimization logic. While centralized optimization offers system-wide control, it lacks the possibility for a modular structure. Agent-based models capture social dynamics but do not provide cost-optimal decision-making frameworks. Cooperative game theory ensures fairness but relies on central agreement and full information sharing, which are difficult to enforce in decentralized energy systems.

In order to construct a model suitable for this research, the non-cooperative game theoretic model is the best fit. The non-cooperative game-theoretic approach allows each Slim Strandnet participant to independently optimize its own objective function while remaining subject to a system-wide coupling constraint. The modular nature of non-cooperative game-theoretic models made this method especially suitable as a simulation model for the operational part of the Slim Strandnet. This flexibility aligns well with the evolving nature of Slim Strandnet, which is still in active development. This modularity allows the model to easily add and eliminate agents without interfering with the global coupling constraint. The following chapter

3 provides a description of how this non-cooperative game theoretic model is structured to the Slim Strandnet case. A detailed description of the model formulation follows in Chapter 4.

2.3.8 Shared Assets in Energy Communities

Shared assets, such as community-scale PV systems, battery storage, and EV chargers, are significant to the functioning of local energy communities. These assets provide collective flexibility, enabling coordinated load shifting, peak shaving, and improved self-consumption. In the academic literature, their role is primarily framed within centralized or distributed optimization routines, where they are controlled by an EMS to achieve system-level performance objectives.

In the two-stage strategy proposed by Mustika et al. (2022), battery storage is included in the centralized optimization as a shared resource used to reduce peak demand and improve overall cost efficiency. Although the battery plays a central role in the operational layer of the model, its ownership structure is not explicitly discussed. The KoR-based allocation distributes total community costs and benefits but does not differentiate outcomes linked to specific shared resources. Similarly, Putratama et al. (2023) incorporate shared flexibility assets, including batteries and EV chargers, into their distributed three-stage framework. These assets are coordinated through internal community prices, used to guide behaviour while ensuring feasibility with local grid constraints.

Across these studies, shared assets are often operationalized to respond to dynamic price signals, charging and discharging based on system-level marginal costs or internal prices derived from grid constraints. Shared assets support cost minimization and flexibility provision, the economic treatment of shared assets is typically embedded in collective allocation mechanisms.

2.4 Literature gap

The academic literature on decentralized energy systems has increasingly addressed topics such as dynamic electricity pricing, cost allocation mechanisms, and agent-based or game-theoretic energy modelling. However, several areas remain underexplored or are explicitly identified in recent studies as directions for future research.

First, while Real-Time Pricing (RTP) and ex-post cost allocation mechanisms such as Keys of Repartition (KoR) have been discussed independently, few studies explore their integration into a unified tariff framework. Mustika et al. (2022) and Putratama et al. (2023) outline two- and three-stage models that incorporate these elements, however, this subject still remains insufficiently studied. Moreover, literature indicates the lack of testing hybrid tariff models under simulated ‘real-world’ conditions and constraint.

Secondly, although ex-post allocation mechanisms like KoR are gaining traction for their potential, the literature does not clearly define how distinct cost components into grid and energy related costs. Both Hupez et al. (2021) and Mustika et al. (2022) propose cost redistribution based on impact factors or coalitional benefits, but they do not operationalize a clear division between energy-related and grid-related cost categories. This remains a methodological grey area in the design of tariffs for local energy systems.

2.5 Scientific Contribution of This Research

Building on the gaps identified in Section 2.4, this thesis contributes to the academic literature by developing and evaluating a hybrid tariff model that integrates dynamic pricing with ex-post allocation, and by testing this framework within a realistically modelled smart grid, the Slim Strandnet. The core scientific contribution lies not only in the theoretical formulation of this dual-layered approach, but in its operational testing under scenario-based simulations that reflect the complexity and heterogeneity of an actual decentralized energy system.

This work is positioned closest to the research of Mustika et al. (2022) and Putratama et al. (2023), who both propose hybrid multi-stage strategies that combine operational optimization with post-settlement allocation mechanisms. Mustika et al. (2022) introduce a two-stage model, where a centralized energy management system is followed by KoR-based billing. Putratama et al. (2023) extend this into a three-stage architecture, including real-time validation and distributed coordination via internal pricing. However, both studies focus primarily on the algorithmic structure of KoR in theoretical communities, and they do not explore the real-world viability of these systems under diverse grid constraints and volatile pricing.

In contrast, this thesis advances the field by applying such a hybrid model within the Slim Strandnet use case, simulating operational constraints and load heterogeneity to evaluate operational outcomes and translate these into diverse cost and benefit distributions, where the added value of cooperation is investigated. A second point of distinction is this thesis' explicit separation of energy-related and grid-related cost domains in the tariff structure. While Hupez et al. (2021) introduce a framework for cost allocation in energy communities based on collective optimisation, the model does not split between two cost streams. This separation enhances both transparency and incentive targeting, particularly in systems involving shared infrastructure.

Furthermore, the model's scenario-based stress testing offers insights into the distributional risks associated with dynamic pricing, particularly for users with low flexibility. These findings reinforce the case for incorporating collective mitigation strategies, such as community billing buffers. While such mechanisms have been discussed conceptually in broader tariff literature (Schittekatte & Batlle, 2023; Weiller & Pollitt, 2013), this thesis is among the first to evaluate their operational logic in a simulated yet realistic setting.

3 Operationalization of the models

Chapter 3 outlines the operationalization of the two central models developed in this thesis, the operational energy model and the tariff model. While these models are conceptually linked, they serve distinct functions and operate sequentially.

3.1 Operational energy model

In practice the Slim Strandnet microgrid actually imposes a cooperative problem where the participants collaborate to obtain operational and financial efficiencies. Thus, in theory the Slim Strandnet microgrid could be taken as one big optimization problem in the conceptualization of the operational energy model, with all agents included. Because, within the operational energy model used to run simulations of the Slim Strandnet, with as bigger goal to analyse the effects of pricing mechanisms, all demand side inputs are given and therefore not flexible. However, in order to create a modular model, which enables for adding and removing agents later on, a non-cooperative game theoretic model is more suitable.

3.1.1 Applied Theory in the Model

The operational energy model in this research builds on the model by Lu et al., (2024) describing a non-cooperative Nash Game between different agents within wholesale as well as retail level. This model is adjusted to fit the operational levels and agents of the slim Strandnet smart grid and is an individual optimization-based approach. This non-cooperative game theoretic model ensures economical rationality for each agent in the model. Moreover, each agent in the model, being a consumer, generator, battery, or else, operates based on an individual objective and individual constraints.

An important feature of the model is the presence of a joint system-level constraint that links all agents within the community. In the case of Slim Strandnet, this constraint corresponds to the contractual import and export capacity limit set by the local distribution system operator, Stedin. This means that, at each time step, the aggregate power exchanged between the community and the external grid must not exceed the maximum capacity defined in the community's grid connection agreement. While each participant independently optimizes its own consumption and flexibility behaviour, the collective feasibility of the system is determined by whether the total community load, including imports and exports, respects this shared boundary condition. This joint constraint plays a central role in coordinating decentralized decisions within the technical limits of the physical infrastructure.

To solve this decentralized optimization problem, the model applies the Alternating Direction Method of Multipliers (ADMM), as introduced by Boyd et al. (2011). ADMM is a distributed optimization algorithm particularly well-suited for problems with separable objectives and coupled constraints, such as the case in Slim Strandnet. The method decomposes the global problem into smaller subproblems, which can be solved independently. These local solutions are then coordinated through iterative updates to ensure system-wide consistency.

Coordination among decentralized agents is enforced through a joint system-level constraint, which is monitored iteratively using two standard convergence metrics, namely, the primal residual and the dual residual. In the context of Slim Strandnet, the global constraint corresponds to the maximum allowable import and export capacity defined in the connection contract with the distribution system operator, Stedin. The primal residual measures the degree to which the current aggregated decisions across all agents violate this joint capacity constraint. In contrast, the dual residual tracks changes in the internal price signal, the Lagrange multiplier, associated with the constraint, thereby indicating the stability and progression of the coordination process.

These residuals serve as convergence indicators for the distributed optimization algorithm. When both fall below predefined tolerance thresholds, the system is considered to have reached a decentralized equilibrium, one in which all individual agent objectives are satisfied while respecting the technical import/export limits of the grid connection.

3.1.2 Conceptual validation of the operational model

This section evaluates whether the model design, assumptions, and theoretical underpinnings are consistent with established scientific and practical knowledge. The modelling framework is reviewed in light of existing literature on decentralized smart grids and tariff simulations (Mustika et al., 2022; Pfenninger et al., 2014), as well as stakeholder input from project partners such as Stedin.

The Slim Strandnet model assumes that participants' electricity consumption follows real smart meter data, without behavioural changes in response to price signals. This reflects standard practice in energy community simulations, where residential and business loads are treated as price-inelastic in the short term. For example, Mustika et al. (2022) use actual household load profiles in a collective self-consumption community without modelling demand response, focusing instead on optimizing local resource usage and billing arrangements. This assumption is justified, as short-term price elasticity for electricity demand is typically low in the absence of active demand-side programs. In the Slim Strandnet context, all participants are business users with fixed contractual consumption commitments, reinforcing the validity of this assumption. Moreover, since participants are currently billed at fixed rates and the model operates at the system level, assuming static demand does not reduce its applicability. Holding demand constant ensures that cost differences are attributable solely to tariff structure and resource coordination, not behavioural uncertainty (Putratama et al., 2023).

The model also assumes a shared community battery and PV system, with benefits allocated to individuals after operational optimization. This separation between operational control and financial settlement is well-supported in the literature. Mustika et al. (2022) propose a two-stage framework where real-time energy management is followed by an ex-post settlement that distributes energy and savings among participants. This enables the community to prioritize collective optimization first, then assign individual benefits fairly. Putratama et al. (2023) expand this into a three-stage strategy that such a structure ensures each member benefits compared to acting alone. Fair benefit allocation is a recurring theme in energy community research. For instance, Gjorgievski et al. (2021) highlight the importance of appropriate sharing mechanisms for maintaining engagement in communities with shared PV resources.

The model's treatment of dynamic Real-Time Pricing (RTP) is also consistent with academic precedent. In the Slim Strandnet framework, RTP affects the system's operational cost but does not alter consumption volumes. This mirrors many studies where price signals guide energy management decisions without assuming user behaviour changes. For example, Putratama et al. (2023) assess different pricing scenarios while holding load profiles constant, allowing the control system to respond instead. The Slim Strandnet model follows this approach, treating short-term demand as price-inelastic and focusing on supply-side adaptation to real-time price signals.

3.2 Hybrid RTP-KoR model

This section systematically explains the foundation and procedures for allocating cost and benefit components according to both academic literature and practices from Dutch Distribution System Operator Stedin, directly involved in the Slim Strandnet project. On the other hand, energy related costs are dealt with by day- ahead prices. In the context of the Slim Strandnet, day-ahead prices are derived from EPEX market prices, which, while not directly reflecting local grid conditions, do provide external signals that encourage participants to shift consumption to periods of higher renewable generation and lower system-wide demand

3.2.1 Cost Allocation Components

The hybrid tariff model allocates system costs across two distinct domains, energy-related costs and grid-related costs. As described earlier, energy-related costs are calculated based on the volume of electricity consumed and the corresponding external day-ahead market prices obtained from the EPEX spot market. Whereas, internal RTP signals serve as steering incentives, encouraging the flexible operation of assets such as battery storage or EV chargers. Although they are derived from external prices, they may diverge in real-time to reflect local grid conditions.

The second cost domain concerns grid-related costs, which reflect the infrastructural burden of energy transport and capacity usage. These costs relate to contractual limits such as kWmax or kWcontract, and are assessed cumulatively across a billing period. Given the collective billing structure of the Slim Strandnet and the diverse load profiles of its participants, this component is allocated using a post-settlement method, KoR. Unlike RTP, KoR does not operate on a real-time basis. Instead, it passively redistributes grid-related costs after operation, based on each participant's measurable contribution to shared capacity usage, such as peak demand.

The costs allocated through the ex-post Keys of Repartition (KoR) method are classified into three categories: one-time costs, recurring operational costs, and performance-based costs. This is made visible in the table below:

One-time costs	**Recurring costs**	**Performance-based costs**
Connection fees	Contracted capacity charges	Peak capacity charges
	Maintenance costs	Transport Fees

Table 8: Overview of different ex-post costs

Table 8 shows the different cost groups and which costs belong to these groups. The first group are the one-time costs, where the connection fees belong to encompass fixed charges related to grid access, either as one-time fees or recurring charges. In cases where participants have significantly varied contracted capacities, allocating costs proportionally to contracted capacity might better reflect individual grid usage (Stedin, 2024). In the Slim Strandnet case there is a relatively big difference in the contracted capacity, therefore these costs are allocated proportionally to the contracted capacity of the participant.

Next to this, the recurring costs group, consisting of maintenance costs and contracted capacity charges, exists. These are the costs that stay relatively stable each billing period. Where the maintenance costs refer to ongoing expenses for the upkeep of the shared community infrastructure. The most common allocation method is treating maintenance as a common good, these costs are distributed equally among all community members to promote fairness and prevent free-riding (Li et al., 2021). The contracted capacity costs represent costs for reserved grid capacity, independent of actual usage. These are allocated capacity-based, where members pay proportional fees according to their contracted peak capacity requirements, thus accurately reflecting individual grid capacity reservations (Energy KnowledgeBase, 2023).

Third, there are the performance based costs, consisting of peak capacity charges and transport fees. These are the performance based costs as these are directly linked with the 'performance' of the smart grid during the billing period. First, the transport fees cover the costs associated with electricity delivery through distribution grids, generally charged per kilowatt-hour. The transport fees are assigned proportionally to energy consumed, reflecting direct correlation with grid usage (Rieger, Jochem, & Fichtner, 2016). Next to this, the peak capacity charges reflect costs related to peak grid load within billing periods, usually the highest hourly or 15-minute interval. These are allocated based on coincident peak responsibility. Where, members are charged based on their relative contribution to the community's maximum demand, incentivizing peak demand reduction behaviours (Rieger et al., 2016; Bâra, Ioniţă, & Borza, 2024).

3.2.2 Benefit Allocation Components

Next to the allocation of costs through the KoR, this mechanism also makes sure that the benefits of the Slim Strandnet microgrid are allocated properly. The benefits allocated through the KoR can also be divided into two different groups, as shown in table 8 below.

Avoided costs	**Energy profits**
Peak demand reduction	Battery profits
Contracted capacity reduction	Solar PV profits

Table 9: Overview of the allocated benefits

Avoided costs, such as reductions in contracted capacity or peak demand, do not appear as separate benefit allocations within the KoR model. Instead, they are implicitly reflected in the lower total cost incurred by the community during the billing period. For example, if the community's peak demand (kWmax) or contracted capacity (kWcontract) is lower than in a previous period, the resulting savings are automatically embedded in the reduced costs section of the KoR bill. These avoided costs are not distributed again, but they can be used as reference metrics to evaluate how individual participants contributed to system-wide efficiency

(Putratama et al., 2023). This approach avoids the risk of double-counting benefits and maintains consistency with cost-reflective allocation logic.

In contrast, energy-based operational profits, such as battery arbitrage gains or PV generation sold, represent actual internal earnings. These are not directly reflected in external billing but are captured through the system's internal optimization. Battery arbitrage revenues, derived from charging at low electricity prices and discharging at high electricity prices, are allocated equally across all participants due to shared ownership. Similarly, PV generation can be sold when there is more generation than demand, note that this can, in periods with negative electricity prices, cost the Slim Strandnet money instead of yielding money. A more detailed overview of where the different costs and benefits stem from and how these are dominantly allocated within the literature can be found in Appendix A.

4. Method

4.1 Introduction

This chapter presents the methodological design used to investigate and construct both an operational energy model and a hybrid tariff model for decentralized energy communities. Grounded in theoretical insights from the literature review, this methodology integrates energy system simulation with post-operational cost and benefit allocation. The central focus is the Slim Strandnet project in Scheveningen, the Netherlands.

First, the operational energy model is discussed, including the assumptions, a model description showing the mathematical model including global constraint, the objectives and constraints of the agents, and the optimization method, followed by the validation of the model. The next section of the method belongs to the hybrid tariff model, which is conceptualized and the mathematics behind the model are shown and explained.

The research adopts a interdisciplinary research approach, combining qualitative input from project stakeholders and scientific literature with quantitative modelling and scenario-based simulations. The primary objective is to evaluate the feasibility of a tariff design that integrates dynamic pricing, for behavioural steering of consumers and flex assets and Keys of Repartition for ex-post redistribution of system costs and benefits. To address this, two interconnected models are developed and applied within this methodology:

An operational energy model, designed to simulate the energy flows and system behaviour of the Slim Strandnet under different tariff regimes and operational constraints.

A hybrid tariff model, constructed to allocate financial outcomes ex-post. It includes a formulation of dynamic pricing and a Keys of Repartition framework to divide both the communal costs and benefits in a fair and explainable manner.

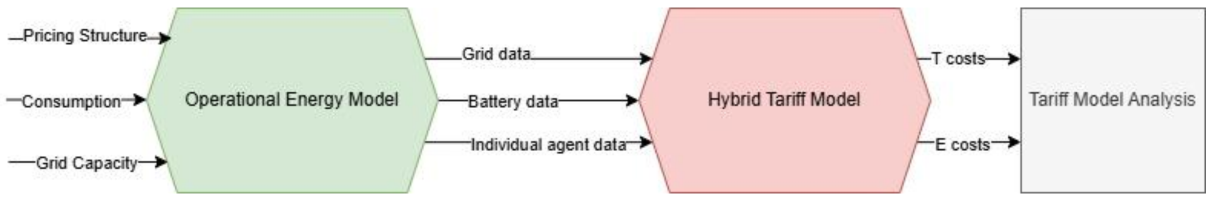


Figure 3: Schematic overview of the flow from operational to hybrid tariff model

As illustrated in Figure 3, the operational energy model receives inputs including day-ahead price signals, individual consumption profiles, and the contracted grid capacity with the DSO (Stedin). The model simulates real-time energy flows and internal price signals (RTP), coordinating the operation of shared assets such as the community battery and EV chargers. Once the simulation is complete, relevant output data, including grid usage, battery dispatch, and participant-specific consumption dynamics, is transferred to the hybrid tariff model.

Within the hybrid tariff model, these outputs are used to construct two distinct billing components: energy-related costs (E costs), based on actual consumption priced at day-ahead market rates, and grid-related costs (T costs), allocated ex-post via the Keys of Repartition

(KoR) method. This separation ensures that each cost category is treated with a mechanism appropriate to its nature: market-based for energy, and impact-based for infrastructure usage.

By applying this layered modelling framework to the Slim Strandnet use case, this research offers an interdisciplinary and operationally grounded approach for evaluating transparent and fair tariff structures in decentralized grid environments. The methodology enables a detailed analysis of behavioural incentives, cost distribution, and the interaction between system-level optimization and participant fairness.

4.2 Operational Energy Model

4.2.1 Introduction

The Operational Energy Model developed in this research serves as a core analytical tool to simulate the physical and economic behaviour of the Slim Strandnet microgrid. Its primary purpose is to evaluate the operational effects of varying tariff structures, asset configurations, and scenario conditions, thus enabling a robust assessment of the proposed hybrid tariff model's technical and economic feasibility.

The model is grounded in the interdisciplinary framework outlined in Chapters 2 and 3 and was built upon a foundational structure presented by my supervisor, Dr.ir. K. (Kenneth) Bruninx, of the Faculty of Technology, Policy and Management, section Energy and Industry. This foundation provided the backbone for the decentralized optimization architecture developed in this thesis.

Structurally, the model adopts a non-cooperative game-theoretic approach in which each participant (agent) independently optimizes its own energy use and flexibility within predefined constraints and objectives. These local optimizations are coordinated using the Alternating Direction Method of Multipliers (ADMM), a distributed optimization method that facilitates convergence to a system-wide equilibrium. A central feature of the coordination is a global constraint that reflects the community's contracted import/export limit with the DSO, ensuring that, at every time step, the total net load of the community remains within feasible operational boundaries.

The model explicitly includes realistic asset-level parameters such as technology efficiencies, charging and discharging limits, and grid constraints. It operates at a 15-minute resolution, in alignment with standard market data intervals, as EPEX day-ahead prices as of June, 2025 (Slim Strandnet Project Group, 2025), allowing for a reliable simulation of real-world conditions. Through this design, the model supports detailed scenario-based analyses, exploring how pricing structures, network constraints, and grid interactions affect the Slim Strandnet's operational outcomes.

4.2.2 Internal Energy Price Formation and Function

Within the operational energy model, the internal energy price, also referred to as Real-Time Pricing, plays a central role in the real-time coordination of shared flexible assets in the Slim Strandnet microgrid. This price signal is generated internally by the energy management system during optimization and is used to steer assets such as the community battery and electric vehicle chargers. It is important to emphasize that this internal RTP is not visible to participants and is not used for billing.

In contrast, participants are exposed only to day-ahead market prices, which serve two purposes, namely, they steer user behaviour, and they form the basis for billing. These day-ahead prices are fixed ex-ante and reflect expected external market-wide supply and demand.

Internally, each agent in the Slim Strandnet independently optimizes its operational behaviour based on local constraints and objectives. These decisions are coordinated through the ADMM, with all agents subject to a global constraint: the contractual import/export capacity limit of the Slim Strandnet connection to the public grid. The internal RTP arises as the dual variable (shadow price) of this constraint. The internal RTP equals the day-ahead price when the joint constraint is not binding, when the community is operating broadly within its import/export limits. In this case, the cost of supplying or consuming an additional unit of electricity is determined solely by the external market. However, when the joint constraint becomes active the internal RTP diverges from the day-ahead price, reflecting the increasing scarcity, or surplus, of energy within the community. This deviation prompts the EMS to adjust shared asset operation, such as discharging the battery to alleviate stress on the grid.

In summary, the internal energy price acts as an operational signal used only within the EMS to coordinate flexible resources, ensuring the feasibility of decentralized optimization under physical constraints. Consumers interact only with day-ahead prices, which remain stable throughout the billing cycle. The responsiveness of internal RTP to system constraints is explored further in Section 4.4.2.

4.3 Model Description

This section details the mathematical structure underlying the operational energy model developed for the Slim Strandnet microgrid. The model is formulated as a decentralized optimization framework, where each agent independently addresses its own optimization problem, governed by individual constraints and objectives. These independent optimizations are intrinsically interconnected through global coupling constraints that ensure system-wide feasibility and coherence.

The primary objective of this section is to explicitly present and explain the mathematical optimization problems each agent solves. Furthermore, the critical global constraints will be explained. This interconnected system forms a complex optimization problem, necessitating an efficient solution method. Consequently, this research utilizes the ADMM algorithm, referencing the approach described by Boyd et al. (2011), to iteratively converge towards an equilibrium solution.

To facilitate understanding, an overview of the symbols used within the model, along with their corresponding definitions, is provided in the nomenclature in the beginning of this Thesis.

4.3.1 Description of the community manager

The community manager acts as the grid agent and serves as the interface between the internal decentralized energy community and the external electricity grid. It is responsible for importing energy when internal supply is insufficient and exporting surplus energy when local production exceeds demand. As such, the grid agent plays a central role in ensuring that residual energy imbalances within the community are resolved in real time. While the system must remain physically balanced at each timestep, this energy balance is not enforced through a standalone equality constraint. Instead, it is maintained implicitly by the grid agent, whose import and export actions compensate for the net internal surplus or deficit. The only explicitly enforced system-level constraint is the maximum allowed import/export capacity, which defines the global constraint in this decentralized model.

$$\boldsymbol{\sum\nolimits_{\in Agents} g(t) = 0 \qquad \forall t \in T}$$

This Energy balance constraint above makes sure that the sum of all generations g(t) is 0, which means that the grid manager is responsible to create an energy balance. The grid manager does this by the needs of importing when demand is higher than supply, and exporting when supply is bigger than demand. This energy balance constraint ensures that, at each timestep, the net energy surplus or deficit within the microgrid is balanced through import or export actions performed by the grid manager. While each agent independently optimizes its own behaviour, it is the grid manager that maintains overall system balance by adjusting grid exchanges.

The objective of the community manager is to minimize the net cost of external grid interactions, taking into account both market prices and internal system coordination signals. Specifically, the agent optimizes the amount of energy to import and export, subject to capacity constraints, while also responding to the internal price signal λ that emerges from the optimization process. This internal price represents the marginal value of energy within the community.

The decision variables are:

- g import: electricity imported from the national grid at time t
- g export: electricity exported to the grid at time t

Objective function:

$$\boldsymbol{min \sum_{t \in T} Import_{B(t)} \cdot g_{import(t)} - Export_{B(t)} \cdot g_{export(t)} - \lambda(t) \cdot (g_{import(t)} - g_{export(t)}\,))}$$

Where:

- **Import_B(t)** is the price of importing electricity from the grid
- **Export_B(t)** is the price received for exporting electricity to the grid
- **g_import(t)** and **g_export(t)** are the import/export flows
- **λ(t)** is the internal electricity price at time (t)

This formulation ensures that the grid agent responds to both external market signals and internal price incentives, promoting economic efficiency in grid usage.

The internal term λ(t)·(g import(t)−g export(t) represents the value of the grid agent’s action from the community's perspective, ensuring that the external exchange decisions are economically consistent with the internal energy balance.

Constraints:

$$\mathbf{0 \leq g_{import(t)} \leq GridCapacity(t)}$$

$$\mathbf{0 \leq g_{export(t)} \leq GridCapacity(t)}$$

These ensure the grid connection is not overloaded in either direction.

4.3.2 Description of the global constraint

The global constraint in the operational energy model reflects the physical and contractual import/export capacity limit of the Slim Strandnet microgrid's connection to the national electricity grid, as agreed with the distribution system operator (DSO), Stedin. This constraint ensures that the total net exchange of electricity with the external grid remains within allowable boundaries at every timestep, thereby preserving operational feasibility.

Mathematically, the global constraint can be formulated as:

$$-\mathbf{GridCapacity} \leq \mathbf{g\_import} - \mathbf{g\_export} \leq \mathbf{GridCapacity} \qquad \forall\ \mathbf{t} \in \mathbf{T}$$

Where:

- g_import is the total electricity imported from the grid at time t
- g_export is the total electricity exported to the grid at time t
- GridCapacity is the symmetric import/export limit defined by the DSO

This constraint couples all agents in the model by limiting their aggregate net interaction with the external grid. While each agent independently optimizes its behaviour, their collective impact must not exceed the maximum allowed grid exchange. This structure is enforced centrally by the Energy Management System and provides the main system-level coordination mechanism in the decentralized model.

The internal price signal λ(t) arises as the dual variable of this global constraint. Economically, λ(t) reflects the marginal value of increasing the available import/export capacity each timestep, in other words, how valuable one additional unit of energy import or export would be, given the current system state. This price signal is used internally to steer shared flexible assets such as batteries and EV chargers.

This global constraint is closely linked to the operation of the grid agent, described in Section 4.3.1. The grid agent is responsible for executing the actual import and export decisions that determine whether this constraint is active. When the constraint becomes binding, the internal price λ(t) typically diverges from the external day-ahead price.

4.3.3 Description of the consumer Agent

The consumer agent represents a non-flexible electricity user within the Slim Strandnet microgrid. These agents do not optimize their electricity consumption in response to price signals but instead follow a fixed demand profile over time. Their role in the model is to introduce a static energy load that must be met through internal generation, storage, or external grid import.

Although the consumer does not actively respond to internal price signals, the optimization framework assigns a cost to its consumption using the internal energy price λ(t), which reflects the system-wide marginal value of electricity at each time step. This formulation ensures that the consumer's demand contributes appropriately to the total cost function of the decentralized system and participates in balancing via coordination with other agents.

Objective function:

$$\boldsymbol{min} \sum_{\boldsymbol{t} \in \boldsymbol{T}} -\boldsymbol{\lambda}(\boldsymbol{t}) \cdot \boldsymbol{g}(\boldsymbol{t})$$

Where:

- g(t) is the net energy generation
- λ(t) is the internal electricity price at time t

Because demand is fixed, the consumer agent does not have decision variables. Instead, its consumption is included in the global coordination through the internal price λ, which balances all agent interactions.

Constraint:

$$\boldsymbol{g}(\boldsymbol{t}) \leq -\boldsymbol{D}(\boldsymbol{t}), \qquad \forall \boldsymbol{t} \in \boldsymbol{T}$$

Where:

- D(t) is the consumer's electricity demand at time t
- This constraint ensures that the net energy generation cannot exceed what would be possible given the consumer's demand profile

This constraint ensures that the consumer can only withdraw electricity up to its known demand value, and not inject energy into the system. In practice, this is equivalent to a static constraint that reflects the consumer's passive role in the system.

While the internal price λ(t) appears in the cost function of this agent for modelling consistency, the consumer itself is not exposed to λ(t). It is billed using day-ahead prices, which are handled separately in the tariff model described in Chapter 5.

4.3.4 Description of the generator Agent

In the Slim Strandnet model, the only energy-producing unit is a shared solar PV system. This agent represents a passive, zero-marginal-cost generator whose output depends solely on external conditions such as solar irradiance. All other energy is either supplied by the community manager or handled by storage agents. As such, the generator agent plays a supportive role in reducing the need for external energy and lowering system-wide costs.

Solar PV has no fuel or variable cost, its production is costless in operational terms. However, for modelling consistency and coordination, its output is still priced internally using the EMS-derived internal price $\lambda(t)$. This allows the optimization framework to assign a marginal value to PV production and incentivize its use when available.

Objective function:

$$\boldsymbol{min} \sum_{\boldsymbol{t \in T}} \boldsymbol{B(t) \cdot g(t) - \lambda \cdot g(t)}$$

Where:

- **g(t)** is the amount of energy generated at time **t**
- **B(t)** is the time-varying linear cost of generation
- **λ(t)** is the internal electricity price at time **t**

This objective maximizes the value of generation to the system by assigning a negative cost to solar energy production at times when $\lambda(t)$ is high, reflecting internal demand or constraints. Due to the fact that the objective is minimized this maximizes the value from generation.

Constraint:

$$\boldsymbol{g(t) \leq AC(t), \forall t \in T}$$

Where:

- **AC(t)** is the available generation capacity at time **t**, determined by external factors such as solar irradiance and installed capacity limits.

This constraint ensures that solar generation does not exceed what is technically available at each timestep. The PV agent does not participate in strategic decision-making; it simply injects energy when available, with its contribution coordinated by the EMS through $\lambda(t)$.

While the generator's output is valued internally at $\lambda(t)$, this internal price is not used for billing. The benefits of local PV generation are distributed via the ex-post cost allocation model described in Chapter 5.

4.3.5 Description of the Battery Agent

The battery agent represents a shared, stationary energy storage system within the Slim Strandnet microgrid. It plays a crucial role in enhancing operational flexibility by shifting energy consumption across time. The battery is centrally managed by the EMS and responds to the internal electricity price signal $\lambda(t)$, which reflects system-level marginal cost conditions. Its function is to charge during low-price periods and discharge during high-price periods, thereby reducing grid stress and minimizing operational costs.

The battery's objective is to minimize the net cost of energy transactions, expressed as:

Objective function:

$$\boldsymbol{min} \sum_{t \in T} -\boldsymbol{\lambda} \cdot (\boldsymbol{d}(\boldsymbol{t}) - \boldsymbol{c}(\boldsymbol{t}))$$

Where:

- **d(t)** is the energy discharged at time **t**
- **c(t)** is the energy charged at time **t**
- **λ(t)** is the internal electricity price at time **t**

This objective encourages economically efficient operation: the battery charges when prices are low and discharges when prices are high, without speculative behaviour, as it is a shared asset optimized for community-wide benefit.

Constraints:

$$\boldsymbol{SOC}(\boldsymbol{t}) = \boldsymbol{SOC}(\boldsymbol{t} - \boldsymbol{1}) + \boldsymbol{\eta} \cdot \boldsymbol{c}(\boldsymbol{t}) - \frac{\boldsymbol{d}(\boldsymbol{t})}{\boldsymbol{\eta}}$$

Where:

- **SOC(t)** is the state of charge at time **t**
- **η** is the round-trip efficiency factor

To ensure cyclic operation, the battery must return to its initial state at the end of the simulation:

$$\boldsymbol{SOC}(\boldsymbol{1}) = \boldsymbol{SOC}(\boldsymbol{T}) + \boldsymbol{\eta} \cdot \boldsymbol{c}(\boldsymbol{1}) - \frac{\boldsymbol{d}(\boldsymbol{1})}{\boldsymbol{\eta}}$$

This constraint ensures that the battery returns to its initial state of charge at the end of the simulation period, allowing for continuous cyclic operation.

$$\boldsymbol{g}(\boldsymbol{t}) = \boldsymbol{d}(\boldsymbol{t}) - \boldsymbol{c}(\boldsymbol{t}), \quad \forall \boldsymbol{t} \in \boldsymbol{T}$$
$$\boldsymbol{0} \leq \boldsymbol{c}(\boldsymbol{t}) \leq \boldsymbol{Cmax}$$

$$0 \le d(t) \le Dmax$$
$$0 \le SOC(t) \le SOCmax$$

These constraints ensure that the battery operates within its physical limits for charging rate, discharging rate, and storage capacity.

4.3.6 Description of the Electric Vehicle Charger Agent

The electric vehicle (EV) charger agent models the charging behaviour of a mobile storage asset that is connected to the Slim Strandnet microgrid for a limited time. Unlike stationary batteries, EVs do not return energy to the system once they depart. Therefore, any energy charged into the EV battery is treated as a net withdrawal from the system.

The EV charger is managed centrally by the EMS and responds to the internal electricity price signal $\lambda(t)$, optimizing when to charge based on system-wide conditions. Its objective is to minimize the total cost of charging over the time horizon:

Objective function:

$$\boldsymbol{min} \sum_{t \in T} -\boldsymbol{\lambda}(\boldsymbol{t}) \cdot (\boldsymbol{d}(\boldsymbol{t}) - \boldsymbol{c}(\boldsymbol{t}) - \boldsymbol{d\_ev}(\boldsymbol{t}))$$

Where:

- **λ(t)** is the internal electricity price at time **t**
- **c** is the energy charged into the EV charger
- **d** is the energy discharged from the EV charger back to the system
- **d_ev** is the energy which permanently leaves the microgrid

This objective reflects the EV charger's preference to charge when prices are low. The term d_ev incurs a cost because it represents energy that leaves the community permanently, while d (discharge) offers cost savings if energy is returned during high-price periods. This formulation encourages the EV charger to operate in a cost-effective way, primarily charging during periods of lower prices.

Constraints:

$$\boldsymbol{SOC}(\boldsymbol{t}) = \boldsymbol{SOC}(\boldsymbol{t}-\boldsymbol{1}) + \boldsymbol{\eta} \cdot \boldsymbol{c}(\boldsymbol{t}) - \frac{\boldsymbol{d}(\boldsymbol{t})}{\boldsymbol{\eta}} - \boldsymbol{d}_{\boldsymbol{ev}(\boldsymbol{t})}$$

Where:

- **SOC(t)** is the vehicle's state of charge at time **t**
- **c(t)** and **d(t)** are the charged and discharged energy
- **d_ev(t)** represents energy transferred into the EV battery and removed from the system
- **η** is the efficiency factor

$$\boldsymbol{g}(\boldsymbol{t}) = \boldsymbol{d}(\boldsymbol{t}) - \boldsymbol{c}(\boldsymbol{t}) - \boldsymbol{d\_ev}(\boldsymbol{t})$$

This constraint defines the total net demand that the EV charger places on the system, incorporating internal battery movement and final vehicle charging.

$$\mathbf{0 \leq c(t) \leq Cmax}$$
$$\mathbf{0 \leq d(t) \leq Dmax}$$
$$\mathbf{0 \leq SOC(t) \leq SOCmax}$$
$$\mathbf{0 \leq d\_ev(t) \leq D\_evmax}$$

These constraints ensure that the EV charger operates within its technical limits. The charger's behaviour supports grid flexibility by allowing load shifting in response to internal system conditions.

4.4 Model Validation

The model has undergone a two-stage validation process to ensure its credibility and relevance, namely, conceptual and operational validation:

4.4.1 Conceptual Validation

The conceptual validation of the operational energy model including its theoretical foundation, structure, and core assumptions is provided in Section 3.1.2. That section reviews how the model aligns with scientific literature and practical constraints relevant to the Slim Strandnet context. This includes justification for key modelling choices such as the assumption of fixed demand profiles, the use of internal price signals for coordinating shared assets, and the separation between operational decision-making and ex-post settlement.

This validation step assessed whether the model's architecture and assumptions are grounded in accepted scientific and practical insights. The modelling framework was evaluated in light of existing literature on decentralized smart grid operation and tariff design (Mustika et al., 2022; Pfenninger et al., 2014), as well as stakeholder feedback from project partners such as Stedin.

4.4.2 Operational Validation

The second validation phase evaluates whether the simulation model functions as intended under varying operational conditions. This involves a set of internal scenario analyses to verify that the model behaves consistently with expectations, including under edge-case and stress-test conditions. To assess the operational validity of the microgrid coordination logic, a simplified case study is developed and presented in Appendix B. This proof-of-concept scenario enables clear observation of the model's internal mechanisms and agent interactions in a controlled environment. The setup includes representative consumers, generation from solar PV, and shared flexibility assets such as batteries.

A key focus of the operational validation is the model's treatment of the internal energy price $\lambda(t)$. As explained in Section 4.2.2, this internal price signal emerges as the dual variable of the global import/export constraint, which limits the net power exchange with the external grid. It reflects the marginal value of electricity within the microgrid at each time step and can deviate from the external market price when the grid constraint becomes active.

To test this mechanism, a temporary grid capacity constraint is introduced during the morning peak hours (08:00–10:00). The results confirm that the internal price mechanism responds correctly: $\lambda(t)$ rises above the external day-ahead price during the constraint period, signalling internal scarcity. In response, the battery agent discharges energy, helping to relieve pressure on the grid and restore system feasibility. During unconstrained hours, $\lambda(t)$ remains equal to the external price, as there is no internal congestion or coordination need. This behaviour confirms that the pricing mechanism supports decentralized control in a manner consistent with system-level constraints.

A snapshot from the operational validation results is provided in Appendix B.

Internal Energy Price and Capacity Constraints

Figure 4 illustrates the evolution of the internal energy price $\lambda(t)$ within the Slim Strandnet microgrid over a representative 24-hour simulation period. For most of the day, the internal price remains constant at €75 per MWh, which aligns with the external day-ahead contract price. This stability reflects unconstrained operation, where the grid capacity is sufficient to meet internal demand, and the EMS does not need to coordinate additional flexibility.

However, a clear deviation occurs at time steps T = 8 and T = 9, during which the available grid capacity is temporarily reduced from 700 kW to 50 kW. This artificial constraint is introduced to test the internal coordination response. As expected, the internal price rises sharply during these periods, reaching €130 per MWh, signalling internal scarcity and prompting shared flexibility assets, such as the battery, to discharge.

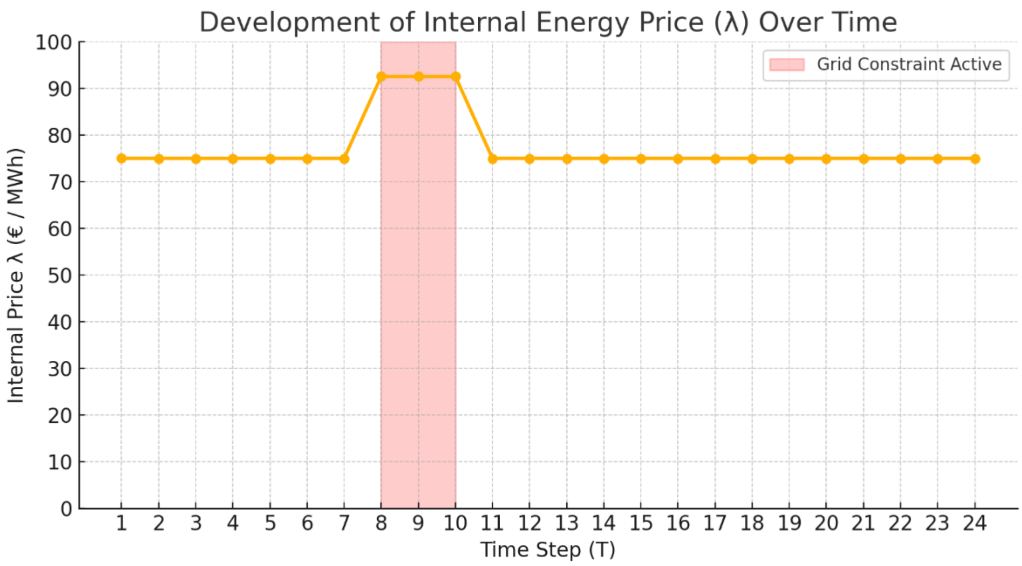


Figure 4: Development of the internal energy price in the operational validation

Scenario variations further explore the system's sensitivity to reduced flexibility and prolonged constraint durations. When battery capacity is reduced or the grid restriction is extended, the internal price rises more steeply and remains elevated for longer. These outcomes confirm that the pricing mechanism correctly signals stress and drives system adaptation.

Overall, the operational validation confirms that the model captures the dynamic interactions between internal price formation, agent behaviour, and physical grid limits. The internal price acts as an effective decentralized coordination tool, adapting in response to system stress without imposing hard consumption constraints. This validates the model's potential for use in more complex smart grid applications explored in the subsequent chapters.

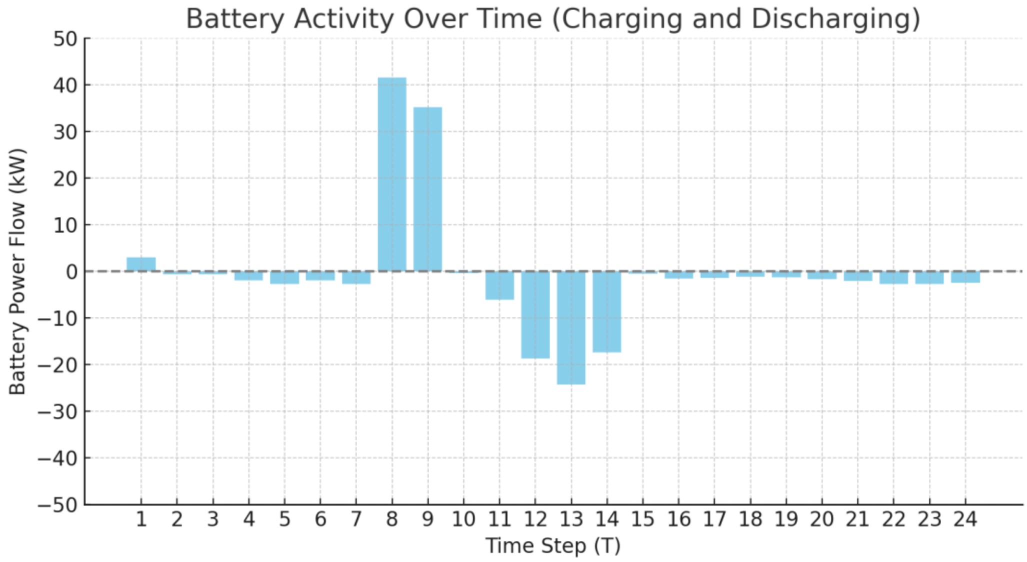


Figure 5: Battery activity during times of active grid constraint

Figure 5 illustrates the charging and discharging behaviour of the community battery across a 24-hour simulation horizon. The battery's operation is guided by the internal electricity price $\lambda(t)$, as generated by the optimization model. During most time steps, the battery remains largely inactive or exhibits modest charging or discharging activity, reflecting stable internal prices and sufficient system flexibility.

However, a notable change occurs during time steps 8 to 10, which coincide with a temporary grid import/export constraint introduced to test the model's coordination logic. In this period, the internal energy price spikes significantly (as shown in Figure 4), reflecting localized scarcity. In response, the battery begins to discharge energy aggressively, particularly at timestep 8 (over 41 kW) and timestep 9 (over 35 kW), helping to alleviate internal grid stress by supplying power to meet demand internally rather than relying on constrained external imports.

This behaviour confirms the intended functionality of the EMS coordination system. The battery discharges when internal prices are high and charges during low-price periods. These patterns support demand flattening, improve grid utilization, and validate the model's ability to reflect real-time optimization under constraints.

Overall, the simulation confirms that the battery responds appropriately to price-based coordination signals, providing time-shifting flexibility that supports operational resilience within the Slim Strandnet microgrid.

4.5 Hybrid Tariff Model

The design of an effective and equitable tariff model lies at the heart of this research. Based on insights from the literature review and the validation of the operational energy model, this section introduces the conceptual and mathematical foundation of the hybrid tariff model developed for the Slim Strandnet use case. The model is structured to achieve two key objectives, namely, to encourage real-time behavioural adjustment through price-based incentives and to ensure fairness in the allocation of costs and benefits after system operation.

This is achieved by combining dynamic pricing as an active, ex-ante steering mechanism with the Keys of Repartition as an ex-post method for cost and benefit redistribution. The hybrid structure addresses several limitations identified in the literature. While RTP improves operational efficiency and incentivizes flexible consumption (Srinivasan et al., 2017; Zhao et al., 2021), it can expose inflexible users to disproportionate financial risks (Eid et al., 2016; Schittekatte & Batlle, 2023). On the other hand, static ex-post allocation mechanisms lacks the ability to guide user behaviour during system operation.

By integrating both components, the hybrid tariff model supports real-time responsiveness through market signals while preserving fairness through measured impact-based redistribution. This dual-layered design aligns with key principles of decentralized smart grid operation, as emphasised by Mustika et al. (2022) and Putratama et al. (2023).

4.5.1 Conceptual Foundation of the Hybrid RTP–KoR Model

The hybrid RTP–KoR tariff model is structured in two complementary layers:

Layer 1 Dynamic Pricing:

During operation, each participant is exposed to external day-ahead electricity market prices, which are communicated in advance. These prices act as behavioural steering signals, encouraging participants to shift or reduce consumption during high-cost periods. This price exposure supports real-time alignment with broader grid conditions, leveraging market incentives to promote cost-efficient and grid-friendly consumption patterns. In the Slim Strandnet context, this is made feasible by advanced metering infrastructure and an engaged group of business participants capable of responding to such signals.

Layer 2 Keys of Repartition:

After the billing period, the Keys of Repartition mechanism is applied to fairly allocate grid-related costs and collective benefits. This includes contracted and peak capacity charges, transport fees, and shared asset-related operational costs or revenues. Rather than assigning these charges purely based on volume or static ratios, KoR uses observed operational indicators to allocate costs and benefits in proportion to each participant's system impact.

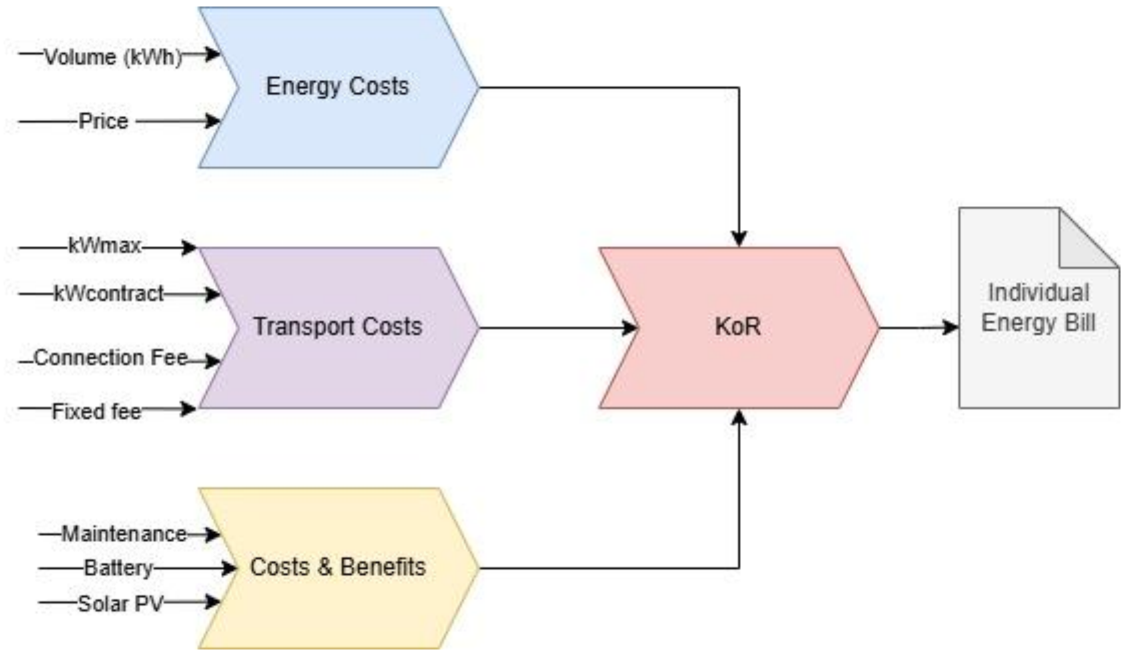


Figure 6: Schematic overview of the working of the RTP-KoR hybrid tariff model

Figure 6 illustrates the core structure of the hybrid tariff model, combining the external price-based energy billing with an ex-post redistribution mechanism for shared costs and benefits via KoR.

The model processes three primary cost and benefit streams:

Energy Costs: Variable costs calculated by multiplying each participant's electricity consumption (in kWh) by the applicable day-ahead market prices. These costs are assigned individually and directly reflect consumption patterns.

Transport Costs: Charges related to grid usage, including contracted capacity and peak-based tariffs, which are aggregated and distributed across the community using KoR.

Shared Costs and Benefits: Includes operation and maintenance of shared assets, and any earnings or costs they generate. These are also allocated via KoR based on measurable contributions or participation indicators.

The KoR module determines each participant's fair share of the collective cost and benefit components based on these indicators. The final output is an Individual Energy Bill that combines both direct energy usage charges based on day-ahead prices, and allocated shares of collective costs and benefits based on KoR logic. This hybrid process ensures that short-term economic efficiency and long-term fairness are jointly embedded in the Slim Strandnet's tariff structure.

4.5.2 Mathematical Formulation of Keys of Repartition

Decentralized energy communities, such as the Slimme Strandnet, create opportunities for collective efficiency gains that extend beyond what individual users could achieve independently. The hybrid tariff model developed in this research enables these shared benefits to be captured and redistributed fairly through the ex-post Keys of Repartition (KoR) mechanism.

At the operational level, shared assets such as the community battery and PV system contribute to overall system performance by reducing external grid imports during high-price periods and absorbing surplus generation. The resulting financial gains—such as battery arbitrage profits or avoided grid costs due to PV self-consumption are treated as community-level benefits and allocated across participants in the billing stage.

Additionally, the community benefits from coincidence effects, where the aggregated system peak demand (kW_max) is lower than the sum of individual participant peaks. This effect reduces the required contracted grid capacity, thereby lowering transport-related costs. KoR enables the allocation of these indirect benefits by distributing avoided costs based on each participant's relative contribution to the collective peak. To operationalize contracted capacity reduction at the community level, the Slim Strandnet coordination model sets a group-level kW_contract threshold. Flexibility resources are scheduled to ensure that this threshold is not exceeded, thereby enabling collective savings on transport and capacity charges.

In summary, the hybrid model not only incentivizes individual behavioural response through day-ahead price exposure but also ensures that users benefit from broader community-level efficiencies via KoR. This dual mechanism increases the attractiveness of smart grid participation by recognizing both direct and indirect contributions in a fair and transparent way.

To ensure financial consistency, the hybrid model is designed to be budget-neutral. This means that the sum of all individual participant bills equals the total costs incurred by the Slim Strandnet energy system during the billing period. This is achieved in two steps. First, all cost components, transport fees, and shared asset costs or benefits are calculated at the system level using operational data. Second, these total values are fully and exclusively allocated to participants using the Keys of Repartition mechanism.

The KoR framework redistributes existing system costs based on observed contributions, but does not create surplus or deficit. As a result, the individual bills produced after allocation collectively sum to the actual system expenditure, maintaining financial integrity within the community billing model. In order to allocate these costs and benefits in a good manner, a good foundation needs to be constructed as a basis of the model.

The KoR allocation of costs and benefits within the local smart grid will be as follows:

$$Total\ Payment = Total\ KoR\ Costs - Total\ KoR\ Benefits$$

Total KoR costs:

$$Total\ KoR\ Costs = Cmaint + Cconn + Ctrans + Ckwmax + Ckwcontract$$

Total KoR Benefits

$$Total\ KoR\ Benefits = Bbattery + Bsolarpv$$

Where:

- Cmaint = maintenance cost share
- Cconn = connection fee
- Ctrans = transport fee (volume-based)
- CkWmax = share of measured peak load cost
- CkWcontract = share of reserved capacity cost

And:

- Bbattery = share of battery savings/revenues
- BsolarPV = share of PV generation or export value

All components are computed ex-post, using operational data from the simulation model, based on information retrieved from scientific articles in the literature review, using the following methods:

Cost Components

Cmaint: Maintenance costs are allocated equally among participants, reflecting the equal access to and collective ownership of shared infrastructure (Li, Wei, & Chen, 2021; Stedin, 2024).

$$C_{\text{maint},i} = \frac{C_{\text{maint}}^{\text{total}}}{N}$$

Cconn: Connection fees are allocated in proportion to the contracted capacity, in line with standard DSO statements for when there are big differences between the users (Stedin, 2024).

$$C_{\text{conn},i} = \frac{C_{\text{conn}}^{\text{total}}}{N}$$

Ctrans: Transport costs are allocated proportionally to each participant’s energy usage volume over the billing period, as these costs scale linearly with consumption and reflect actual grid utilization (Rieger, Jochem, & Fichtner, 2016).

$$C_{\text{trans},i} = C_{\text{trans}}^{\text{total}} \cdot \frac{E_i}{E^{\text{total}}}$$

CkWmax: Peak demand charges are allocated proportionally to each participant's contribution to the community-wide maximum demand, measured during the peak event. This coincident peak responsibility approach incentivizes individual peak reduction (Bâra et al., 2024). When the collective maximum peak is lower than the sum of individual peaks, the community avoids excess costs. The benefits can in this case be seen as avoided costs and get redistributed through KoR as a reduction in the CkWmax.

$$C_{\text{kWmax},i} = C_{\text{kWmax}}^{\text{total}} \cdot \frac{P_i^{\text{peak}}}{\sum_{j=1}^{N} P_j^{\text{peak}}}$$

CkWcontract: Contracted capacity charges are allocated in proportion to each participant's estimated, based on past data, individual capacity need, as a proxy for their contribution to the required community contract size (Energy KnowledgeBase, 2023; Casalicchio et al., 2022). If the community is able to contract a lower capacity due to demand shifting, increased flex-assets or diversified usage patterns, the resulting reduction in capacity fees becomes an avoided cost. This saving is likewise captured and distributed via KoR seen as a reduction in the below shown calculation.

$$C_{\text{kWcontract},i} = C_{\text{kWcontract}}^{\text{total}} \cdot \frac{C_i^{\text{contract}}}{\sum_{j=1}^{N} C_j^{\text{contract}}}$$

Benefit Components

Bbattery : Battery trading profits are allocated equally among participants, based on the assumption that the battery is communally owned and its resilience and cost benefits are shared equally (Crowley et al., 2025).

$$B_{\text{battery},i} = \frac{B_{\text{battery}}^{\text{total}}}{N}$$

BsolarPV: Solar PV benefits are also allocated equally, reflecting a static percentage scheme commonly used in collective self-consumption models where all participants are considered co-owners of the installation (Galvin, 2020; Claeys et al., 2021).

$$B_{\text{solarPV},i} = \frac{B_{\text{solarPV}}^{\text{total}}}{N}$$

This clear allocation framework enables fair, transparent, and replicable distribution of costs and benefits within the Slim Strandnet community. The actual numeric values of each component will be derived ex-post from operational simulations, allowing dynamic evaluation of various pricing and behaviour scenarios.

5. Slim Strandnet Use Case

5.1 Input data for the use case

The operational energy model used in this study relies on a combination of real-world and simulated data to accurately reflect the behaviour of the Slim Strandnet decentralized energy community.

Consumption Data

Electricity demand data was collected from five active participants in the Slim Strandnet community, located in Scheveningen, The Hague. These include the central operations unit (Bediencentrale), a construction site (Bouwplaats), and three beach restaurants (Strandtenten). The data is anonymized and was accessed through the internal Slim Strandnet database. Originally recorded at one-minute intervals via smart meters, it has been aggregated into 15-minute blocks to align with the upcoming regulatory shift in the Netherlands, where energy billing will be performed in 15-minute intervals starting mid-2025 (Netbeheer Nederland, 2024). Most consumption profiles are available from September 2024, corresponding with the initial connection of each participant to the Slim Strandnet infrastructure.

The model defines three types of consumers, categorized based on their energy consumption patterns:

Type	**Locations**
Type A	Hito, The Shore, Aloha
Type B	Control Center
Type C	Construction Site

Table 10: Overview of the different consumers in the Slim Strandnet case study

Generation Data

Solar photovoltaic (PV) generation is modelled using simulated data based on historic solar irradiance profiles for Scheveningen. While actual solar generation from Slim Strandnet installations is available, a simulated profile offers greater flexibility to test future scenarios, such as expansion in PV capacity. These profiles are aligned with historical sunlight data and validated against observed generation in the area, ensuring consistency. The 15-minute resolution of the PV data matches that of the consumption profiles and enables accurate net-load calculations.

Generator	**Capacity**	**Variable Cost**	**Availability**
Solar Panels	6 kW	€0/kWh	Solar-dependent, fluctuates with solar intensity (Scheveningen)

Table 11: Overview of the generators within the Slim Strandnet use case

Community manager

The community manager functions as the grid agent, which models the connection between the Slimme Strandnet microgrid and the national grid. It manages both energy imports and exports based on system imbalances. The model assumes a maximum contracted capacity of 857 kW, reflecting real-world limitations. The grid connection availability varies depending on the scenario. Although the Slimme Strandnet community currently operates under a disproportional large connection capacity of 857 kW, this study explores the potential benefits of implementing a lowered group transport agreement (GTA) as a future contractual alternative. The GTA is a Dutch regulatory instrument that allows multiple users to share a single contracted grid connection collectively. This mechanism is introduced in the modelling framework to assess its potential to reduce grid-related costs through improved coordination and shared flexibility. The simulated scenarios include capacity limitations to mimic the operational constraints that would exist under a GTA-like arrangement. Pricing mechanisms used in the model include flat tariffs, Time-of-Use, and Real-Time Pricing, enabling analysis of the grid agent's response under different regulatory and market conditions.

Grid	Capacity	Pricing structure	Availability
Grid	857 kW	Flat, ToU & RTP	Availability is based on the capacity constraint, in the scenarios with an active GTA the Grid capacity is reduced as far as possible.

Table 12: Overview of the grid operator properties

Flex Assets Data

The battery storage system used in the model reflects the specifications of the real-life battery installed at the Slim Strandnet site. It has a total capacity of 425 kWh and a maximum power output of 250 kW for both charging and discharging operations. Roundtrip efficiency is assumed to be 85%, consistent with manufacturer specifications and existing literature on lithium-ion battery systems in grid applications (Zakeri & Syri, 2015). The battery is shared among all users in the community and plays a key role in peak shaving and temporal load balancing in the model simulations.

The EV charger in the model reflects the available charging infrastructure at the Slimme Strandnet site. It features a total storage capacity of 260 kWh and a maximum charging power of 44 kW. Discharging into the grid is not modelled, aligning with the typical behaviour of EVs as net consumers rather than sources of power. The charging behaviour follows a set schedule, and once the EV departs, the stored energy is no longer available to the grid. The model incorporates three types of flexible assets: a battery system, EV chargers, and a heat pump.

Asset	Capacity	Charging Power	Discharging Power	Efficiency
Battery1	450 kWh	225 kW	225 kW	85%
EV Charger	260 kWh	44 kW	-	80%

Table 13: Overview of the flex assets in the Slim Strandnet use case

Tariff and Pricing Information

The multi-component tariff structure used in the model is based on official documentation from Stedin (2024), the Dutch distribution system operator responsible for the region. This includes volume-based charges (€/kWh), kW max peak charges, contracted capacity charges, a fixed transport fee, and a connection charge. Energy prices are drawn from multiple sources to simulate various pricing schemes: real-time prices (RTP) are based on historical day-ahead hourly pricing data from the EPEX SPOT exchange, while time-of-use (TOU) and flat tariff schemes replicate the current contractual terms held by the Municipality of The Hague with its energy supplier ENECO. These pricing structures are used to explore the impact of dynamic tariffs on billing outcomes.

Tariff Type	Price Structure
Flat Tariff	€0.135 per kWh (constant rate)
Time-of-Use (ToU)	€0.12 per kWh (low tariff: 23:00–07:00, weekends, special days) | €0.14 per kWh (high tariff: weekdays 07:00–23:00)
Real-Time Pricing	Based on EPEX Day-Ahead hourly market prices

Table 14: Overview of the different tariff types for the Slim Strandnet use case

In the table above the different tariff types are shown with their corresponding price structure inputs.

Cost Element	Tariff Structure
Volume-based charges	€0.0198/kWh (normal and low tariff periods)
Maximum demand (kW max)	€3.10 per kW per month
Contracted capacity (kW contract)	€2.025 per kW per month
Fixed transport fee	€36.75 per month
Connection fee	€1,455.50 per year + one-time fee of €34,002

Table 15: Overview of the different transport costs by Stedin

Above are the transport cost elements and their corresponding pricing structure shown as indicated by the distribution systems operator of the Slim Strandnet, Stedin.

Assumptions and Participant Setup

The simulation assumes fixed consumption patterns, meaning no behavioural demand response flexibility is modelled beyond the operation of shared assets (e.g., battery storage). Solar PV and the battery system are modelled as shared community assets managed collectively by the grid agent. A total of five consumer profiles are modelled, each corresponding to actual Slim Strandnet participants. This setup reflects the physical and operational characteristics of the Slim Strandnet energy community, providing a realistic use-case foundation for scenario analysis.

5.2 Simulation Scenarios

To further investigate the outcomes of the smart grid model under varying tariff conditions and operational constraints eight distinct simulation scenarios were developed. Each scenario was run across three representative months**,** October, December, and March, resulting in 24 simulations in total. These three months are specifically chosen, because each period has its own characteristics due to weather conditions, or business related reasons as more or less tourism for the beach pavilions. There is unfortunately no month in the summer period, this is due to the fact that there was no week with complete information within the summer months.

The three months were chosen for their distinct characteristics:

- **October** reflects moderate energy demand and transitional solar availability.
- **December** captures high winter demand and low PV production.
- **March** represents early spring with emerging solar potential and diverse load patterns.

These timeframes ensure that the model is tested under seasonal variability, while also benefiting from complete and consistent data availability.

Scenario Variables

The scenarios vary along two main dimensions:

1. **Tariff Structure:**
   - **Flat Price:** A constant electricity price per unit of energy throughout the day.
   - **Time-of-Use:** Predefined pricing blocks based on contractual prices.
   - **Real-Time Pricing:** Hourly prices that fluctuate with actual grid or market conditions.
   - **RTP with Price Peaks:** Same as RTP, but includes artificially introduced peak price events.
2. **Group Transport Agreement:**
   - **Without reduction:** No contractual limitation on peak capacity. DSO charges are incurred based on actual kWmax and kWcontract usage.
   - **With reduction:** A capacity-limiting contract is in place to cap grid usage, reducing DSO-related costs for the community. This creates an economic incentive to collectively manage and flatten peaks.

To simulate the group transport contract reduction, the operational model imposes a reduced common grid capacity constraint. This constraint acts as a contractual import/export limit between the Slim Strandnet community and the external grid. The value of this limit is gradually lowered to explore how far the community can reduce its contracted capacity while still operating feasibly.

Feasibility is assessed using the model's ADMM convergence criteria, namely the primal and dual residuals. The grid capacity is iteratively reduced until one of two conditions is met, either the system fails to converge within acceptable tolerances, or constraint violations occur. This process identifies the minimum viable contracted grid capacity that the system can support under the current scenario configuration, and thereby effectively quantifying the potential economic benefit of entering a reduced-capacity group transport agreement.

Scenario Overview and Purpose

Scenario	Purpose
Flat Price, No GTA	Baseline scenario with fixed pricing and no contractual constraints, forms the baseline with zero flexibility incentives.
Flat Price, GTA	Tests the possibility of a capacity cap in an otherwise stable pricing environment. Measures cost-saving potential from peak management alone.
ToU Price, No GTA	Simulates under structured but variable pricing, with no pressure to reduce peak capacity. This is the current situation of Slim Strandnet.
ToU Price, GTA	Combines scheduled price incentives with capacity constraints, investigating what is possible capacity wise right now.
RTP, No GTA	Assesses decentralized response to dynamic, real-time price fluctuations without peak limitations. First step to more dynamical pricing.
RTP, GTA	Integrates real-time price responsiveness with contractual incentives to reduce peak load, representing a fully dynamic and grid-optimized context.
RTP, Price Peaks, No GTA	Introduces extreme price volatility without any formal peak capacity agreement. Tests possibility to battle price peaks as a grid.
RTP, Price Peaks, GTA	Evaluates whether a capacity-constrained contract (GTA) is possible during highly volatile pricing periods.

Table 16: Scenario overview and purpose

To explore the effects of different tariff models and contractual arrangements on energy costs and system efficiency, eight simulation scenarios were constructed. Each scenario represents a unique combination of pricing strategy and grid capacity arrangement. Together, these simulations provide insight into how decentralized energy communities can optimize financial performance while ensuring fairness and resilience. All simulations are based on real consumption data from the Slim Strandnet and use a fixed consumption profile to isolate the effects of pricing and contractual mechanisms.

Scenario 1 – Flat no Cap - Flat Price, No Capacity-Limiting Contract (GTA):

This baseline scenario models a traditional flat pricing scheme without any contractual capacity limitation. It reflects the cost outcomes when each participant pays a constant price per kilowatt-hour (kWh), regardless of the time of day or system load, and the community retains the current contracted grid capacity (857 kW). It serves as a benchmark for evaluating more dynamic strategies.

Scenario 2 – Flat Cap - Flat Price, With GTA:

Scenario 2 retains the flat pricing model but introduces a Capacity-Limiting Contract (GTA), which caps the community's contracted capacity. This tests the economic potential of operating under reduced grid capacity while keeping energy prices static. It highlights the benefit of leveraging load diversity to lower capacity-related costs.

Scenario 3 – ToU no Cap - Time-of-Use (ToU) Price, No GTA:

This scenario introduces time-differentiated pricing (ToU) to reflect current utility tariff structures where prices vary between peak and off-peak hours. However, no capacity limitation is applied, meaning the community continues to pay for the full 857 kW of contracted capacity. It examines how moderate price signals influence cost distribution and system costs under fixed consumption.

Scenario 4 – ToU Cap - ToU Price, With GTA:

Combining ToU pricing with a GTA, this scenario tests whether cost savings from time-varying tariffs can be amplified by reducing grid capacity. It reflects a more advanced operational model where both price signals and grid contract optimization are used to manage costs.

Scenario 5 RTP no Cap - Real-Time Pricing (RTP), No GTA:

Scenario 5 introduces real-time pricing (RTP) based on day-ahead market values (EPEX), offering high temporal granularity and price volatility. Without capacity reduction, this scenario measures the responsiveness of shared infrastructure (such as batteries) to RTP under full grid access. It is critical for understanding how dynamic price signals affect operational behaviour and energy costs.

Scenario 6 – RTP Cap - RTP, With GTA:

This scenario adds a capacity-limiting contract to the RTP environment. It represents the most operationally optimized version of the decentralized grid, where both price volatility and grid constraints are present. It provides key insights into the performance of a hybrid model combining dynamic pricing and strategic contract minimization.

Scenario 7 – Peak no Cap - RTP with Price Peaks, No GTA:

Scenario 7 builds on Scenario 5 by injecting extreme price peaks into the real-time pricing series. These artificial events simulate market shocks or scarcity conditions and test how the absence of flexibility or protective mechanisms (like insurance or caps) can expose inflexible users to high energy costs.

Scenario 8 – Peak Cap - RTP with Price Peaks, With GTA:

This final scenario incorporates both price volatility and capacity limitation. It reflects the most complex market environment, where users face real-time prices, potential price spikes, and grid constraints. It tests the robustness of the hybrid model and highlights the importance of mechanisms like KoR (Keys of Repartition) for fair cost redistribution and risk mitigation.

Real-Time Pricing here refers to the input of Day-ahead prices and the internal coordination by Real Time Pricing (Lambda).

5.3 Results analysis

Transport Costs

This section examines the transport cost components, specifically contracted grid capacity (kWcontract) and measured peak capacity (kWmax), which form a major part of the Dutch distribution tariff structure. These charges are sensitive not only to consumption volume but also to peak load patterns, making them highly relevant for evaluating the impact of local energy coordination.

A key feature investigated in this thesis is the Group Transport Agreement (GTA), which allows the community to share a single grid connection rather than each participant contracting capacity individually. This agreement creates the potential to reduce costs by leveraging diversity in peak demand. Because participants rarely reach their individual maximums at the same time, the coincidence factor lowers the system-wide peak allowing the community to safely contract less grid capacity than the sum of their individual needs.

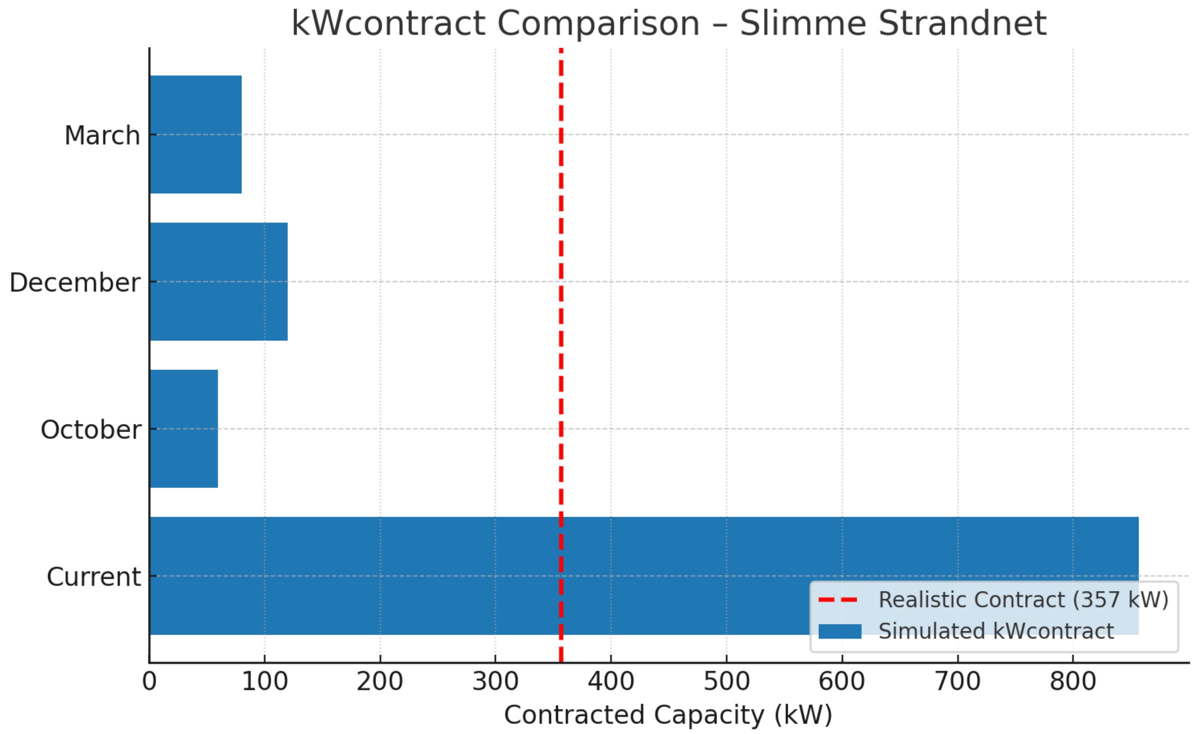


Figure 7: Overview of the kWcontract that the Slim Strandnet now has compared to the simulated months

The currently contracted grid capacity of the Slimme Strandnet is set at 857 kW. This value, however, significantly overestimates actual system needs under present operational conditions. Both the Slimme Strandnet consortium and the local distribution system operator (DSO), Stedin, acknowledge this discrepancy and are actively exploring a more representative and cost-efficient configuration. As a result, a reduction to a realistic contracted capacity of 357 kW has been identified as a near-term operational target.

Figure 7 illustrates not only this adjusted benchmark but also the additional optimization potential revealed by the simulation model. Based on three representative months from different seasons, October, December, and March, the results indicate that the system-wide contracted capacity could, in principle, be lowered even further without breaching system constraints.

This analysis reinforces the central hypothesis of this thesis: that active cooperation within a decentralized smart grid enables tangible financial and infrastructural efficiencies. Even with the more realistic 357 kW contract in place, significant room remains for further improvement through smarter operation and community-level coordination.

Furthermore, by summing the total individual kWmax and kWcontract charges and comparing them with the collective values, we can observe concrete potential financial savings. These differences are the result of shared use of flexible assets and the coincidence factor. Take table 16 down here as proof:

Agent	kWmax (kW)	kWMax (€)	kWcontract (€)
March RTP no Cap			
Grid	115.74	358.78	234.36
Collective consumption	131.63	408.05	266.55
March RTP CAP			
Grid	85.70	265.67	173.54
Collective consumption	131.63	408.05	266.55
December RTP no Cap			
Grid	128.60	398.66	260.41
Collective consumption	163.79	507.75	331.67
December RTP CAP			
Grid	102.84	318.80	208.25
Collective consumption	163.79	507.75	331.67
October RTP no Cap			
Grid	90.67	281.09	183.61
Collective consumption	99.29	307.79	201.06
October RTP CAP			
Grid	59.99	185.97	121.48
Collective consumption	99.29	307.79	201.06

Table 17: Overview of individual grid connections versus collective grid connections

Table 17 presents a comparative overview of the financial outcomes under varying contractual and operational configurations, specifically focusing on the community's peak demand (kWmax) and the corresponding transport-related costs. The table draws a distinction between scenario setups with a standard grid capacity contract and those in which the grid capacity is actively lowered to a feasible operational minimum.

In all Scenario 5 (S5) runs, the system operates under a fixed, non-restricted grid capacity. While participants may still benefit from the coincidence factor, where staggered demand profiles result in a collective peak (kWmax) that is lower than the sum of individual peaks, no explicit contract limitation is imposed. This situation corresponds to a Group Transport Agreement (GTA) being in place, but without capacity reduction. As such, while some efficiency is achieved through load diversity, the contracted capacity remains high, and the associated transport charges are only moderately reduced.

In contrast, Scenario 6 (S6) simulations implement a strategic reduction in grid capacity, simulating the conditions under which the community agrees to lower the kWcontract as much as technically feasible, without violating the energy balance or triggering infeasibility. This is done by introducing a binding grid constraint into the operational model, which requires the system to rely more on internal coordination and flexible assets to maintain balance. As a result, both kWmax and kWcontract values are significantly lower, leading to meaningful reductions in transport-related costs.

This side-by-side comparison reveals the tangible benefits of collective smart grid participation along a spectrum of coordination, namely:

- Without grid capacity reduction (S5): The community benefits from the coincidence factor, but capacity charges remain relatively high.

- With grid capacity reduction (S6): The community proactively minimizes its contracted capacity through internal flexibility, realizing substantial additional financial savings.

This distinction is critical to articulating the value proposition of coordinated operation within a smart grid environment. While group participation through a shared infrastructure, such as a Group Transport Agreement (GTA), already reduces individual exposure to grid-related tariffs by leveraging the coincidence factor, the implementation of a collectively managed and actively constrained grid capacity unlocks additional system-wide efficiencies.

These layered effects are illustrated in Figure 8 below, which compares the measured community-wide kWmax across six scenario configurations. Each scenario includes two bars: one representing the collective sum of individual kWmax values (yellow) and the other reflecting the actual grid kWmax achieved through smart grid coordination (orange).

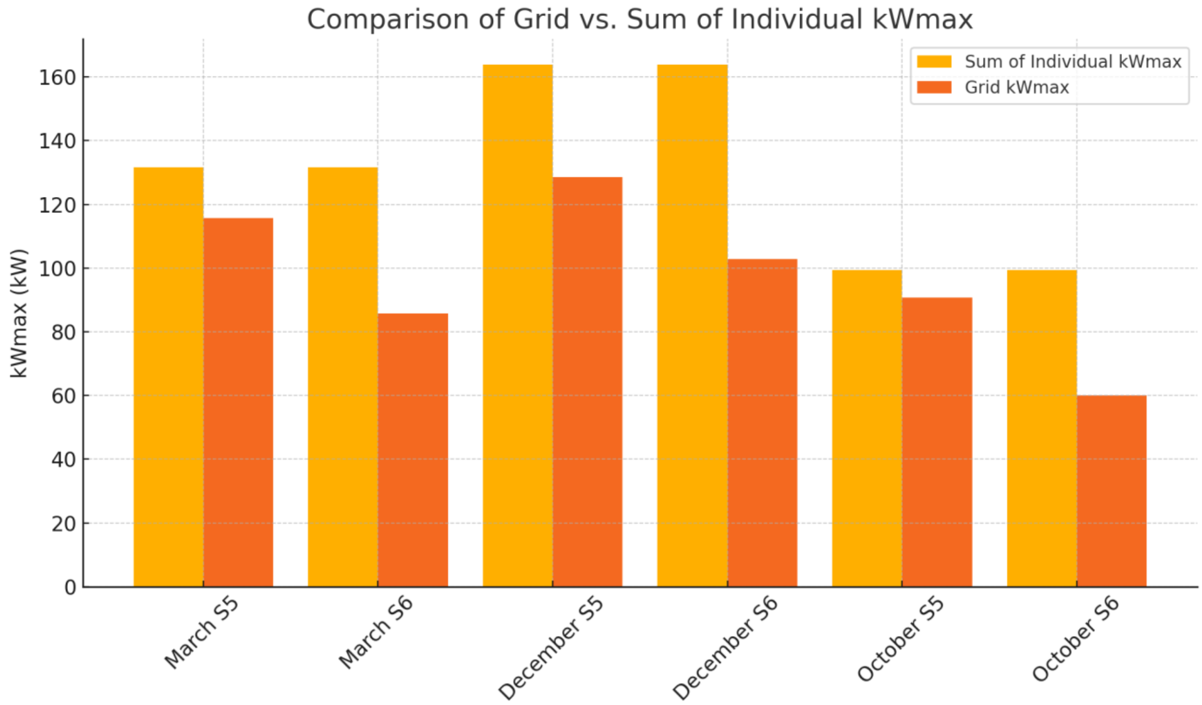


Figure 8: Comparison of Grid vs. Sum of Individual kWmax

The first key observation is that, in every scenario, the yellow bar exceeds the orange bar—demonstrating that even without explicit capacity constraints, operating under a group contract (GTA) provides measurable benefit over individual contracts due to non-coincident peak demand.

Secondly, and even more significantly, the comparison across the orange bars reveals that all Scenario 6 simulations, which include an active grid capacity limitation, result in lower kWmax values than their Scenario 5 counterparts. This clearly shows that smart grid coordination not only allows the community to benefit from group billing but also enables deeper optimization by strategically managing peak demand. Thus, coordinated capacity management yields advantages beyond those of shared infrastructure alone.

How is this possible? The observed reductions in community peak demand under constrained conditions (Scenario 6) are made possible by the strategic deployment of flexible assets, particularly the community battery. When the grid capacity constraint is lowered, the internal price signal (λ) within the optimization framework adjusts accordingly. This elevated internal price serves as a coordination signal, incentivizing the battery to discharge at critical moments, thereby alleviating pressure on the grid and ensuring feasibility of the joint constraint.

Figure 9 below illustrates the total energy charged and discharged by the battery in Scenario 5 (unconstrained) and Scenario 6 (constrained) for the month of March. The data clearly show an increase in both charging and discharging activity in Scenario 6, confirming the more active role of the battery in maintaining grid stability under capacity-limited conditions. This dynamic response to internal pricing is a key feature of smart grid operation and highlights how operational flexibility contributes directly to tariff efficiency.

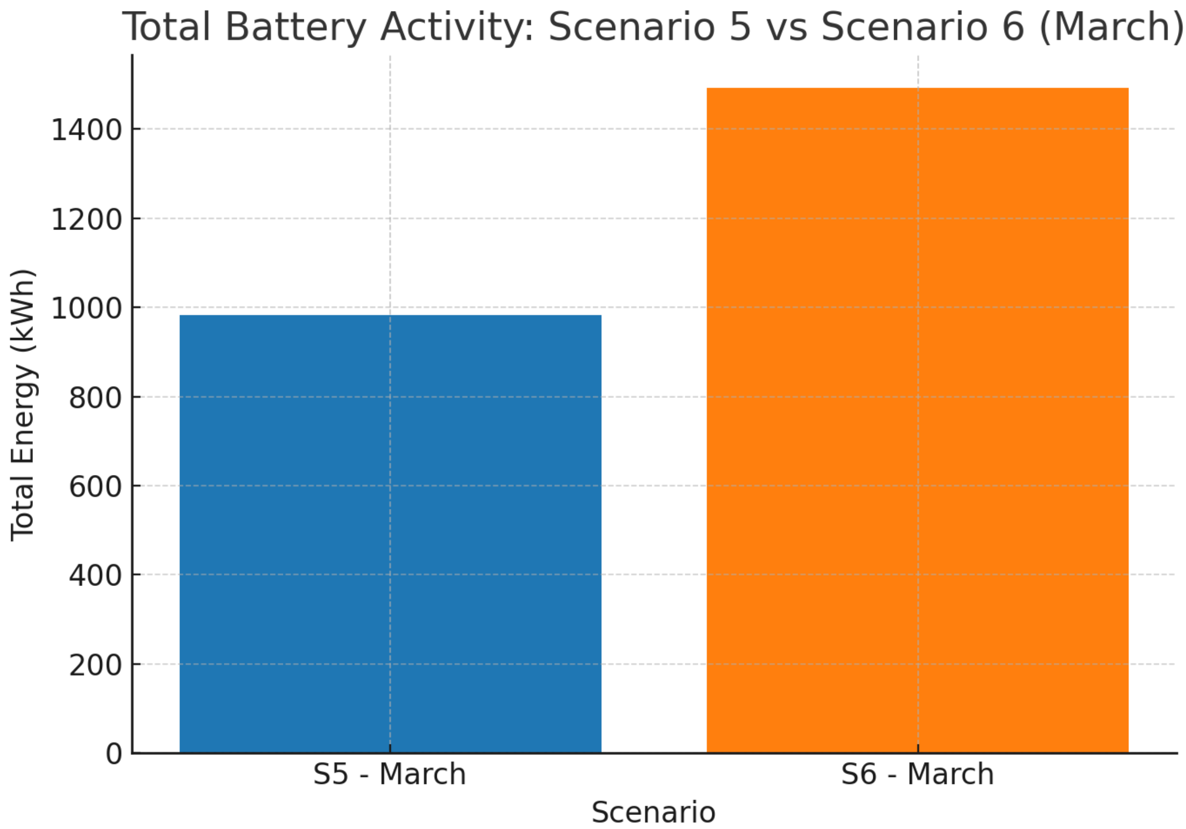


Figure 9: Difference in Battery activity with or without lowered grid capacity

Energy Costs

Energy costs in the simulations are for a large share caused by the pricing strategy that goes into the model as an input, for example if real time pricing has lower prices than time of use pricing this causes a decrease in energy costs. However, while part of this reduction can be attributed to lower real-time wholesale cost prices during the simulated period, this alone does not fully account for the observed differences. The operational energy model can more effectively schedule the charging and discharging of the community battery under real-time pricing. This allows the system to store electricity when prices are low and deploy it to meet demand during expensive periods, thereby reducing reliance on external supply during peak cost intervals.

March								
Total Energy Cost	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8
Battery	0.23	4.81	1.23	3.16	-82.03	-69.64	-421.41	-406.79

Table 18: Overview of the financial impact of the battery usage in March

December								
Total Energy Cost	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8
Battery	0.57	0.60	1.72	1.72	-34.90	-30.86	-365.84	-365.72

Table 19: Overview of the financial impact of the battery usage in December

October								
Total Energy Cost	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8
Battery	0.47	13.69	1.01	7.44	-55.24	-46.96	-411.67	-403.44

Table 20: Overview of the financial impact of the battery usage in October

Above in the tables we can identify the impact of the battery trading (import and export) on the total energy bill for the Slim Strandnet. During the scenario’s with a flat price or time of use pricing the battery is not doing much and even costing the grid some money. However, when the prices get more dynamic in the form of real time pricing, the battery is able to trade due to its own optimization. The impact of the battery on Slim Strandnet is big as it combines two factors, the battery is helping out operationally and next to this is trading on the market to even generate some income.

Price peaks

March				
Total Energy Cost	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Grid	815.77	828.43	1023.66	1037.72
Type A	320.84	320.89	550.61	550.36
Type B	546.38	546.43	839.69	839.35
Type C	55.03	55.08	91.90	91.77
Pv	-24.32	-24.28	-36.97	-36.97
Battery	-82.03	-69.64	-421.41	-406.79
December				
Total Energy Cost	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Grid	1211.41	1215.45	1658.24	1658.35
Type A	357.35	357.35	584.64	584.64
Type B	705.45	705.45	1133.07	1133.07
Type C	222.89	222.89	382.01	382.01
Pv	-39.38	-39.38	-75.64	-75.64
Battery	-34.90	-30.86	-365.84	-365.72
October				
Total Energy Cost	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Grid	502.78	511.06	680.66	688.88
Type A	286.17	286.17	555.84	555.84
Type B	182.01	182.01	337.95	337.95
Type C	115.28	115.28	252.89	252.89
Pv	-25.45	-25.45	-54.35	-54.35
Battery	-55.24	-46.96	-411.67	-403.44

Table 21: Overview of the individual energy costs for Slim Strandnet participants with or without price peaks

The table above highlights the differences between the real-time pricing scenarios 5 and 6 and the price peak scenarios 7 and 8, which are also based on real-time pricing but include unexpected, high-magnitude price spikes introduced at random intervals. These scenarios were designed to simulate the potential volatility inherent in wholesale electricity markets and to assess the resulting impact on both the total energy bill for the Slim Strandnet community and the financial burden experienced by individual participants.

Despite the total energy consumption being held constant across all scenarios, the results reveal a significant increase in energy costs in scenarios 7 and 8 compared to the standard real-time pricing scenarios. This clearly illustrates the sensitivity of financial risk to temporal price volatility, particularly for users with limited flexibility in their consumption patterns. For instance, when comparing scenario 5 (standard RTP without GTA) to scenario 7 (RTP with random price peaks and also without GTA) for the month of October, the energy costs for the control room rose from 182.01 euros to 337.95 euros. This represents an increase of approximately 85.7 percent, despite no change in energy volume or behaviour.

What is important to notice in this table is the influence of the community battery. In the scenario's 5 and 6, the scenario's without price peaks, the battery is doing quite little actually with a reduction on the energy bill of 3% to 12%. However, when comparing this to the price peak scenarios (7 and 8), the battery gained much more attention in terms of capturing the financial risks. By cutting down the total energy bill of the Slim Strandnet with a percentage with percentages between 22% and even 60% in scenario 7 in October. Thus, this shows the importance of the battery as a financial risk mitigating factor, however, unfortunately, the battery is still not able to cover all financial risk due to the price peaks. This strongly indicates and advices for extra risk mitigating mechanisms, such as the in chapter 2 mentioned insurance fund.

These findings underscore the potential financial risks that participants face under highly volatile pricing conditions, particularly those who cannot easily shift or curtail demand in response to short-term market signals. The results also highlight a critical trade-off inherent in adopting real-time pricing models: while they offer substantial savings under normal conditions, they expose users, especially inflexible ones, to cost volatility when prices spike. This reinforces the need for appropriate price security mechanisms or complementary strategies, such as collective billing or internal insurance schemes, to mitigate the disproportionate burden on vulnerable participants.

5.5 Conclusion of Results and Use Case

The results from the Slimme Strandnet simulations demonstrate the incremental value of coordinated energy community design, progressing through three distinct levels of integration. These steps reflect increasing collaboration, technical alignment, and economic optimization within the community, with clear impacts on both energy and transport cost structures. As a leading example Figure 10 below shows the overall expenses for one participant (TypeB) of the Slim Strandnet during the month March. In these expenses a distinction is made between three layers, namely, an individual energy contract, a GTA and a GTA with a lowered collective grid capacity.

March	*TypeB*	*Energy Costs*	*Transport Costs*	*Totaal*
	1 Individual	483.30	429.49	912.79
	2 GTA	483.30	394.85	878.15
	3 GTA CAP	490.76	329.83	820.60

Figure 10: Overview of expenses for one participant

1. **Individual Contracting**

In the first configuration, each participant maintains an individual energy and grid access contract. This structure exposes users to the full cost of both energy procurement and grid transport without benefiting from shared infrastructure or coincident load effects. For participant Type B, this results in a total monthly cost of €912.79 in March, comprising €483.30 in energy costs and €429.49 in transport costs. This baseline scenario reflects the absence of system-level coordination or efficiency.

2. **Group Transport Agreement (GTA)**

In the second step, the Slimme Strandnet adopts a shared grid contract through a Group Transport Agreement. Although participants retain individual consumption profiles, they collectively benefit from the coincidence factor: the statistical diversity in demand patterns leads to a lower aggregated peak (kWmax), reducing the required contracted grid capacity (kWcontract). Consequently, participant Type B sees a cost reduction to €878.15, with transport costs falling to €394.85 and energy costs equal at €483.30.

3. **GTA with Coordinated Grid Capacity Reduction (GTA CAP)**

The third and most sophisticated step introduces active operational coordination to the GTA. By setting a deliberate cap on community grid import capacity within the simulation model, the community requires its flexible assets, particularly the battery, to play a more prominent balancing role. Internal price signals (λ) rise in response to the constraint, triggering battery discharge to maintain system feasibility. As a result, participant Type B experiences further transport cost reduction to €329.83. However, the more frequent use of the battery in high-price periods slightly increases energy costs to €490.76. Nevertheless, the total monthly cost decreases to €820.60, representing a savings of over €92 compared to the individual case.

This progression illustrates that:

- **Step 1 → Step 2 (Individual → GTA):** Delivers savings by leveraging load diversity and a joint grid contract.
- **Step 2 → Step 3 (GTA → GTA CAP):** Unlocks additional savings by using internal flexibility to lower peak imports and contractual capacity.

While energy costs in the final step rise modestly due to the intensified role of battery dispatch under constrained conditions, the net financial benefit remains clear. These findings highlight the strategic value of both institutional cooperation and operational flexibility in decentralized smart grid systems.

6 Discussion

Reflections on the Research Process

A strength of this thesis lies in the iterative, model-driven methodology employed to investigate both operational and economic dimensions of decentralized smart grids. The successful deployment of the model enabled advanced scenario analysis, and more importantly, it became a tool with direct practical utility for the Slim Strandnet project group.

The operational model was used not only for academic simulation, but also to answer real-world questions from the Slim Strandnet stakeholders. These included estimating the minimum feasible grid capacity for collective operation and testing dynamic pricing structures. This level of applied relevance illustrates how academically tools can bridge into practice and support decision-making in emerging decentralized energy communities.

Interpreting Results: From Operational Coordination to Financial Performance

A central aim of this research was to quantify the operational and financial benefits of coordinated energy management in decentralized smart grids. The scenario analysis revealed that collective operation can lead to substantial reductions in transport-related costs, particularly those associated with contracted grid capacity (kWcontract) and measured peak demand (kWmax). This is enabled through the Group Transport Agreement (GTA), the GTA introduces a shared contractual framework where participants can jointly negotiate a kWcontract based on their aggregated, observed peak load, thus offering greater flexibility while still incentivizing collective demand management.

In the most efficient scenarios tested, the Slim Strandnet community was able to operate at just 15% of its currently contracted grid capacity. However, this result should be interpreted in light of two important contextual factors. First, the existing contract of 857 kW is already known by both the community and the DSO to be significantly oversized. A more realistic starting point, currently under discussion, would be approximately 357 kW. Second, this oversized capacity accounts for anticipated future growth in the number of agents and electricity demand. The modular structure of the operational model was designed to reflect and support this ongoing expansion.

Despite these considerations, the findings remain compelling, even in a winter month such as December, the optimized system rarely required more than 130 kW of capacity. These results underscore the value of both load diversity and flexible resources, such as batteries, in flattening peaks and lowering grid dependency. And as we have seen in Figure 8, the grid capacity can even be lower when coordinated action takes place. Because in all lowered contracted grid capacity scenarios the kWmax is lower than the equal scenario (same month) without this lowered contracted grid capacity, indicating even more potential.

Moreover, a key outcome across scenarios was the clear financial advantage of collective contracts over individual contracting. The simulations showed that participants do not reach their demand peaks simultaneously, resulting in a significant “coincidence effect.” By capitalizing on this temporal variation, the community can operate under a much lower collective peak than the sum of its individual maxima, thereby reducing total transport costs and strengthening the case for investing in shared infrastructure and control mechanisms.

However, an important policy consideration must be noted. DSOs are increasingly adapting GTA tariffs to reflect their growing use and the financial implications of the coincidence factor. As a result, GTA-based billing is expected to become more expensive in the coming years. While this might reduce some of the projected financial gains, it also reinforces the necessity for communities like Slim Strandnet to fully activate and coordinate flexibility assets. The benefits of cooperation, in this sense, are not eliminated by pricing reforms but made even more essential.

Integrating CBCs: Combining Contractual Strategies

The scenario results highlight that significant cost reductions can be achieved not only through group contracting (GTA) but more decisively by actively managing and reducing the community's contracted grid capacity. This approach replaces the need for formal capacity-restricting mechanisms like CBCs by leveraging operational coordination and flexible assets to naturally limit peak loads.

Rather than layering multiple contractual instruments, the Slim Strandnet model demonstrates that a single, well-calibrated GTA, accompanied by a carefully chosen grid capacity limit, can already unlock substantial transport cost savings. By setting a lower kWcontract ex-ante and using internal coordination, the community is able to respect lower grid constraints.

This strategy emphasizes a proactive rather than reactive approach, namely, instead of relying on emergency capacity limitations triggered under CBCs, the Slim Strandnet operates continuously within a tighter capacity envelope. Internal system mechanisms, such as the use of batteries and EV chargers, are mobilized in response to price signals (λ), ensuring that the grid connection remains within contractual bounds while maintaining energy service levels.

The operational model suggests that this capacity optimization can be made dynamic. As seasonal data improves, future GTA configurations may adjust the kWcontract by month or quarter, reflecting expected load variations and improving alignment with actual grid needs. Such a modular and adaptive GTA framework presents a scalable alternative to legacy CBC strategies, aligning better with the flexible, decentralized nature of smart grids.

Implications for Tariff Model Design

The integration of day-ahead pricing within the hybrid tariff model introduced substantial variability in user-level energy costs, particularly during simulated high-price events. This volatility disproportionately affected inflexible users where observed cost increases reached up to 85% in extreme cases. Although shared assets like the battery were able to mitigate a portion of this risk by shifting demand away from peak periods, they could not fully eliminate financial exposure.

These findings underline the importance of embedding structured financial risk-mitigation strategies into tariff design. While collective billing, provides a foundational mechanism for distributing volatility across participants, additional instruments are needed to safeguard vulnerable users. One such mechanism is the implementation of a community reserve fund, designed to buffer unexpected price shocks through pooled contributions.

Future tariff models for decentralized energy systems should not treat such mechanisms as optional add-ons, but as integral components of a socially robust design. By proactively addressing price risk, these features can enhance user trust, participation, and the long-term viability of smart grid communities. Such a fund could easily be implemented in the KoR phase of the Tariff model as an additional Cost / Benefit component. Where each participant pays a fee to the insurance, and in cases where prices rise above certain levels, this will be deducted as a benefit in the KoR formula.

Academical Reflections

This thesis journey has been one of the most demanding and ultimately rewarding experiences of my academic career. I can state that I have never before been tested, intellectually, emotionally, and practically over such a continuous period of time. Working intensively on a single complex challenge for more than half a year, namely the design and implementation of a scientifically grounded tariff model for the Slim Strandnet project, has pushed me beyond what I initially thought I was capable of also in terms of stress.

At the start, I could not have foreseen the direction this research would take. The problem was not simply technical or mathematical, it was also conceptual and highly contextual. The project required me to navigate academic literature, communicate with real-world stakeholders, and translate abstract theory into operational models with direct relevance. The scope of the task expanded far beyond what I had expected, and with it, my skills and mindset had to evolve.

Throughout the process, I developed a deep appreciation for the iterative nature of academic investigation. Many parts of the model had to be revisited, challenged, and restructured, often after weeks of work, once their theoretical or practical limitations became clear. This taught me the value of intellectual humility and adaptability. I learned how to embrace uncertainty and revision not as setbacks, but as necessary components of academic rigour and model integrity.

On a more personal level, I learned about persistence and working under pressure. There were certainly moments of frustration, fatigue, and even self-doubt. But overcoming these challenges brought a sense of resilience and pride that I will carry forward into my future academic and professional work.

In conclusion, this thesis has not only advanced my academic skills in modelling, analysis, and critical thinking, but also shaped me as a more resilient, reflective, and interdisciplinary thinker. It has shown me what it means to work at the edge of complexity, and what a ride it was.

Conclusional reflection

This research has operationalized a complex, hybrid tariff model within the practical context of the Slim Strandnet energy community. By integrating dynamic RTP and day-ahead pricing with an ex-post cost allocation mechanism (KoR). The findings confirm that smart coordination, enabled by shared assets and structured through layered pricing strategies, not only enhances system performance but also safeguards fairness in cost and benefit distribution. In particular, the combination of RTP with KoR allows real-time behavioural incentives to coexist with long-term equitable billing.

The approach developed here can serve as a blueprint for similar communities seeking to balance innovation and transparency. Ultimately, this thesis contributes not only to the academic discourse on smart grid tariff design but also to the practical advancement future-ready energy systems.

7 Conclusion

This thesis has developed a robust and fair tariff model for a decentralized smart grid, using the Slim Strandnet as a real-world use case. The central research question was:

"How can a tariff model be developed for a local smart grid such as 'Slim Strandnet' that incentivizes sustainable energy use and fairly distributes costs and benefits based on each participant's contribution to balancing locally generated energy supply and demand?"

To answer this question, a hybrid tariff model was designed that combines Dynamic pricing with the Keys of Repartition (KoR) mechanism. The model was empirically validated through eight simulation scenarios over three months, offering quantitative evidence of both operational and financial outcomes. This conclusion synthesizes the findings by directly addressing the three sub-questions.

Sub-question 1: *What are the potential financial and operational benefits of collaboration within a local energy community compared to individual energy contracts?*

The results provide strong evidence that collaboration within a local energy community unlocks significant operational efficiencies and financial benefits. By coordinating electricity consumption and optimizing shared flexible assets such as community batteries and EV chargers, participants can collectively reduce both peak demand (kW_max) and contracted grid capacity (kW_contract).

The scenario analysis highlights that, in lowered contractual grid capacity scenarios (2, 4, 6, and 8), the required contracted grid capacity was reduced by up to 85% compared to the current 857 kW connection, without compromising operational feasibility. Even during high-demand periods such as December, the system maintained balance with a capacity as low as 128.55 kW, indicating substantial room for contractual renegotiation. Similar to the findings of this thesis, recent literature confirms that collaboration within a local energy community enables substantial reductions in contracted grid capacity and peak demand. Putratama et al. (2023) demonstrate that a coordinated three-stage management strategy achieved up to 30% individual cost reductions while maintaining operational feasibility. Mustika et al. (2022) provide additional validation, showing that a two-stage model, where energy management and billing are decoupled, led to a global community bill reduction of 11.7%, with individual participant savings ranging from 11% to 19%. These results affirm the efficiency gains from shared asset utilization and coordinated demand response.

Due to the coincidence factor, where individual consumption peaks do not align simultaneously, even collective billing without explicit coordination already resulted in lower total system costs than the sum of individual contracts. This highlights the inherent efficiency of community-based grid access. These findings confirm that organizing into a GTA is not only technically feasible but also economically beneficial. Furthermore, the research suggests that communities could pursue even more cost-effective strategies by combining a GTA with a dynamically optimized contracted capacity. This could include seasonal or event-based adjustments, allowing communities to strike a balance between long-term tariff reductions and short-term operational reliability.

Sub-question 2*: What existing methods for cost allocation and price setting within the scientific literature are applicable to local smart grids like Slim Strandnet?*

The results of this thesis demonstrate that a hybrid tariff model, combining Dynamic pricing (RTP and day-ahead pricing) and Keys of Repartition (KoR), is both theoretically grounded in the literature and practically effective for decentralized energy communities like Slim Strandnet. However, the way in which these methods were applied in this research differs in several important respects from how they are often conceptualized in the academic literature.

In the operational model developed for this study, external day-ahead prices were used as the basis for final billing. These prices function as ex-ante signals to inform participants about expected cost conditions and steer their energy consumption behaviour accordingly. In contrast, internal RTP signals, emerging endogenously within the community energy model, were used purely to steer the operation of flexible assets such as the battery and EV chargers. This distinction between external (billing) and internal (coordination) pricing is rarely made explicit in the literature but proved to be analytically and operationally useful in this context.

KoR was then applied ex-post to allocate grid-related costs and shared asset benefits based on objective indicators like peak contributions and proportional usage. Importantly, avoided costs were not redistributed to prevent double counting a refinement not always addressed in similar studies. Mustika et al. (2022) emphasize the importance of separating internal operational coordination from external billing mechanisms, noting this dual structure enhances both transparency and responsiveness.

Sub-question 3: *What alternative factors should be considered in designing a tariff model that provides financial security for participants in Slim Strandnet?*

The simulations in this thesis confirmed that while dynamic pricing offers strong operational and economic advantages, it also introduces financial risk, especially for participants with limited flexibility. This challenge is well-documented in the literature, and the findings here underscore the need to complement dynamic pricing with targeted risk-mitigation mechanisms. The necessity of layered risk protection is further stressed by Hupez et al. (2021), who demonstrate that fairness-enhancing mechanisms such as cooperative Nash-based or Shapley-based allocations can prevent strategic defection and support continued community participation during volatile pricing events.

Within the Slim Strandnet, collective billing already serves as a foundational mechanism that allows energy to be procured and billed at the group level. This shared contractual structure not only improves access to coordinated grid usage but also enables the implementation of internal financial protection tools. One such mechanism explored in this research is the use of a community reserve fund, an insurance-like buffer that could be integrated into the KoR layer. Though not yet implemented in Slim Strandnet, the concept is compatible with its existing billing structure and aligns with mechanisms proposed in recent studies.

Furthermore, the results showed that shared flexibility assets, particularly the battery, already played a strong role in reducing community exposure to high energy prices during volatile market periods. For example, in October's peak price scenarios, battery activity significantly dampened the financial burden for the community. However, these system-level tools alone were insufficient to fully eliminate risk exposure, especially under conditions of extreme price spikes or when flexibility was saturated.

Main Research Question: *"How can a tariff model be developed for a local smart grid such as 'Slim Strandnet' that incentivizes sustainable energy use and fairly distributes costs and benefits based on each participant's contribution to balancing locally generated energy supply and demand?"*

The most effective tariff model for Slim Strandnet is a hybrid, multi-layered structure that integrates real-time incentives with ex-post fairness and embedded risk protection. It consists of the following key components:

Real-Time Pricing (RTP) / Day-ahead pricing, functions as a dynamic steering signal that incentivizes participants to adjust their energy use in real time, aligning local demand with supply fluctuations. This encourages use of local generation, off-peak consumption, and deployment of flexibility assets like batteries.

Keys of Repartition (KoR), to ensure fairness, KoR allocates collective costs and benefits based on measurable operational contributions. This mechanism redistributes value post-operation, correcting for inherent differences in flexibility and promoting equity.

Group Transport Agreement, the tariff model leverages a collective transport contract that allows the Slim Strandnet community to contract grid capacity jointly. This enables peak load sharing, exploits the coincidence factor, and reduces both measured (kWmax) and contracted (kWcontract) grid costs.

Capacity Coordination via Flexibility, the model goes further by enabling participants to actively lower the kWcontract through coordination and strategic operation of flexibility assets. Simulations demonstrated that this cooperative strategy can reduce grid connection needs by over 80% without operational failure, even in high-demand months like December.

The result is a replicable, modular tariff model that reflects the operational, and economic complexities of local smart grids. It successfully incentivizes sustainable behaviour and transparently distributes collective value. This hybrid RTP–KoR framework offers a strong pathway for Slim Strandnet and similar smart grids to scale from pilots to robust components of the energy system.

Appendix A

Hybrid RTP-KoR model

Keys of Repartition models define how collective costs and benefits within energy communities are distributed among their members. Such models are essential for decentralized smart grids and local energy communities, as they ensure fairness, transparency, and effective incentive structures (Li, Wei, & Chen, 2021; Stedin, 2024). This section systematically explains the rationale and methodologies for allocating each cost and benefit component according to both academic literature and practices from Dutch Distribution System Operator Stedin, directly involved in the Slim Strandnet project.

3.2.1 Cost Allocation Components

Maintenance Costs (C_maint), refer to ongoing expenses for the operation and upkeep of shared community infrastructure such as PV systems, battery, and local electrical networks. There are two primary allocation methods:

Equal Allocation**:** Treating maintenance as a common good, these costs are distributed equally among all community members to promote fairness and prevent free-riding (Li et al., 2021).

Usage-Based Allocation**:** Costs are proportionally assigned based on each member's utilization, thus aligning financial responsibility with actual infrastructure wear and tear (Li et al., 2021).

In practice, equal distribution through general network charges is used to simplify administrative processes (Stedin, 2024).

Connection Fees (C_conn), encompass fixed charges related to grid access, either as one-time fees or recurring charges. The allocation typically follows:

Equal Allocation**:** Reflecting uniform access, connection fees are commonly shared equally per connection point, consistent with DSO regulatory practices (Stedin, 2024).

Capacity-Based Allocation**:** In cases where participants have significantly varied contracted capacities, allocating costs proportionally to contracted capacity might better reflect individual grid usage (Stedin, 2024).

Generally, DSOs advocate an equal distribution method for simplicity and fairness unless significant capacity variations exist (Stedin, 2024).

Transport Fees (C_trans), cover the costs associated with electricity delivery through distribution grids, generally charged per kilowatt-hour (kWh). Allocation method:

Consumption-Based Allocation**:** Universally supported by academic literature and DSO practices, this approach assigns costs proportionally to energy consumed, reflecting direct correlation with grid usage (Rieger, Jochem, & Fichtner, 2016; Casalicchio, Nicolosi, & Rosato, 2022).

This method is preferred for its transparency, administrative simplicity, and alignment with cost causation principles (Rieger et al., 2016).

Peak Capacity Charges (C_kWmax), reflect costs related to peak grid load within billing periods, usually the highest hourly or 15-minute interval. Allocation typically involves:

Coincident Peak Responsibility: Members are charged based on their relative contribution to the community's maximum demand, incentivizing peak demand reduction behaviours (Rieger et al., 2016; Bâra, Ioniţă, & Borza, 2024).

Such an approach encourages load shifting and energy efficiency practices among participants.

Contracted Capacity Charges (C_kWcontract), represent costs for reserved grid capacity, independent of actual usage. Allocation methods include:

Capacity-Based Allocation**:** Members pay proportional fees according to their contracted or expected peak capacity requirements, thus accurately reflecting individual grid capacity reservations (Energy KnowledgeBase, 2023; Stedin, 2024).

Using contracted or historical peak demands is viewed as the most equitable and precise method (Stedin, 2024).

3.2.2 Benefit Allocation Components

Peak Demand Reduction Savings (B_reduction_kWmax), arise when communities effectively reduce peak energy demand, thus avoiding associated charges or infrastructure upgrade costs. Allocation strategies include:

Contribution-Based Allocation**:** Savings are proportionally allocated to members based on their direct contributions to demand reduction, incentivizing active participation in demand response initiatives (Casalicchio et al., 2022; Bâra et al., 2024).

This method aligns member incentives with community efficiency goals.

Contracted Capacity Reduction Savings (B_reduction_kWcontract), occur when communities collectively require lower contracted capacities, typically due to diversified load patterns or distributed generation. Allocation methods include:

Peak Responsibility Allocation**:** Savings are distributed based on how each member's individual profile reduces the overall community's contracted capacity needs, encouraging demand smoothing behaviours (Casalicchio et al., 2022).

This precise allocation method accurately rewards contributions to reduced collective capacity requirements.

Battery Storage Benefits (B_battery), offer peak shaving, energy arbitrage, backup power, and improved renewable self-consumption and even the possibility of energy trading with Real-Time pricing, generating various financial benefits. Allocation strategies include:

Equal Allocation: Appropriate when batteries serve the entire community equally, especially if collectively funded, reflecting a communal asset (Crowley et al., 2025).

Because the battery is a common good, the most reasonable allocation method is an equal distribution of benefits.

Solar Photovoltaic (PV) Benefits (B_solarPV), PV installations reduce grid reliance and provide potential revenue from surplus energy. Allocation methods encompass:

Static Percentage Allocation**:** Fixed shares assigned to all members equally, suitable for communities prioritizing simplicity and perceived equity (Galvin, 2024).

Investment-Based Allocation: Benefits proportionally distributed according to financial investment, ensuring economic fairness relative to individual contributions.

For the Slim Strandnet, where the PV panels are a common good, equal static percentage allocation is the best reasonable allocation method.

3.2.3 Conclusion

Designing an equitable and efficient Keys of Repartition (KoR) mechanism in decentralized energy communities requires a careful balance between practicality, transparency, and economic optimization. Academic literature supports cost allocations to reflect cost-causation principles such as usage-based distribution for energy-related costs and contribution-based allocations for peak and capacity-related charges (Bâra et al., 2024; Casalicchio et al., 2022). Moreover, benefits should be shared according to participants' actual contributions to collective savings, while also ensuring a baseline level of equity to promote inclusivity and long-term engagement within the community (Bâra et al., 2024).

European distribution system operators, including Stedin in the Netherlands, have also emphasized the need to revise existing cost allocation models to ensure that users who provide grid-supporting services are appropriately rewarded, while vulnerable users are not disproportionately burdened (Stedin, 2024). These evolving tariff considerations reflect a broader recognition of the value of cooperative action in distributed energy systems.

KoR Component	Allocation Method
C_maint	Equal
C_conn	Equal
C_trans	Consumption-based (kWh)
C_kWmax	Contribution-based
C_kWcontract	Contribution-based
B_reduction_kWmax	Contribution-based
B_reduction_kWcontract	Contribution-based
B_battery	Equal
B_solarPV	Equal

Table 22: Overview of the different KoR methods with corresponding allocation method

The reviewed literature converge on key principles for designing KoR frameworks: maintenance and connection fees should be distributed equally; transport costs should align with energy consumption; and peak-related and capacity charges should be allocated based on responsibility for system load (Galvin, 2024; Rieger et al., 2016). In terms of benefit distribution, proportional sharing of the gains from collective actions such as battery optimization, and solar PV production is widely supported as a fair and incentive-compatible strategy (Bâra et al., 2024; Casalicchio et al., 2022; Galvin, 2024). Whereas, kWmax is calculated every billing period and kWcontract, having a cost component and a benefit component which are every billing period the same if nothing changed to the contract, so less dynamic.

Appendix B Operational validation

Case study Simplification of the Smart Grid Model

Objective

This case study presents a simplified implementation of the smart grid model, serving as an illustration of its practical operation. Building on the model description from the previous chapter, the study aims to clarify the functional characteristics of the model. Additionally, it plays a role in model validation, systematically verifying whether the model outcomes align with theoretical expectations.

The decision to use a simplified version of the model allows for a clearer analysis and interpretation of its underlying mechanisms. While this version is less complex than a full-scale implementation, it retains essential components, including consumers, generators, and flexible assets, ensuring representativeness. Moreover, this simplified approach is designed so that its results can be extrapolated to more complex applications.

The following sections provide a detailed overview of the different model components and the scenario in which the case study is conducted.

Components of the Illustrative Study

Consumers

The model defines four types of consumers, categorized based on their energy consumption patterns:

Type	Example Locations
Type A	Hito, The Shore, Aloha
Type B	Control Center
Type C	SAP, Beach Stadium
Type D	Construction Site

Table 1: Overview of Consumer Types

Type	Description
Type A	This consumer group (beach pavilions) exhibits a predictable energy consumption pattern, with peaks during lunch (12:00 - 14:00) and dinner (18:00 - 21:00).
Type B	The Control Center has a highly regular and constant consumption pattern, distinct from other types.
Type C	Temporary connections, characterized by seasonal and fluctuating energy consumption.
Type D	Construction sites, displaying a different consumption pattern from other types, with higher energy demand during the workday, fluctuating based on construction activities.

Table 2: Overview of Consumer Characteristics

Generators

The model includes two energy sources, one renewable and one grid-based:

Generator	Capacity	Variable Cost	Availability
Solar Panels	200 kW	€0/MWh	Solar-dependent, fluctuates with solar intensity

Table 23: Generator operational validation

Grid	**700 kW (restricted to 50 kW from 08:00 - 10:00)**	**€75/MWh**	**Continuously available, but limited during the morning peak (08:00 - 10:00)**

Table 24: Grid manager input data operational validation

Flexible Assets

The model incorporates three types of flexible assets: a battery system, EV chargers, and a heat pump.

Asset	Capacity	Charging Power	Discharging Power	Efficiency
Battery1	450 kW	225 kWh	225 kWh	90%
EV Charger	260 kW	44 kWh	44 kWh	90%
Heat Pump	200 kW	30 kWh	30 kWh	Standby losses: 5%

Table 25: Flexible assets operational validation

This case study provides a structured analysis of how different consumer types, energy sources, and flexibility assets interact within the local smart grid environment. The simplified approach allows for a clear demonstration of model functionality, ensuring that its behaviour aligns with theoretical predictions before extending the model to more complex implementations.

Scenario for the Illustrative Study

In this illustrative study, the model is simulated over a 24-hour period, consisting of 24 time steps of one hour each. The input data used are fictitious yet realistic, designed to ensure clarity and comprehensibility in analysing the model's behaviour. Consumer consumption patterns are derived from average existing data, though they have been simplified to represent typical daily energy usage. The generator capacities are based on standard specifications, while variable costs are estimated using average energy prices in the Netherlands. The availability of solar energy is modelled according to average solar irradiation levels in the region. For the battery, input parameters are chosen to reflect characteristics representative of a system with comparable size and efficiency.

This scenario incorporates a capacity constraint during the morning peak, where maximum grid capacity is reduced from 700 kW to 50 kW between 08:00 and 10:00. This specific scenario is chosen because smart grid collectives can financially benefit from adapting to such capacity restrictions.

The model distinguishes between presence factors and consumption quantities in the input. Presence factors represent the availability of different energy sources and storage options per time step, while consumption quantities reflect the energy demand of various consumer groups. These consumption values are scaled based on the number of consumers within each group. A complete overview of the input data used in this study is provided in Appendix A.

Hypothesis of Expected Outcomes

This study analyses a scenario where grid capacity is limited to 50 kW during the morning peak (08:00 - 10:00). During the remaining hours, the available capacity is 700 kW, meaning no grid constraints are expected outside of the morning peak period.

During the morning peak, solar energy availability is low, implying that the smart grid will rely heavily on the limited grid capacity of 50 kW. Without additional flexibility measures, it is anticipated that the total energy demand will not be fully met.

To maintain energy supply continuity within the network, it is expected that available flexible assets, particularly the battery, will play an active role. The battery will discharge stored electricity to compensate for the temporary capacity restriction, allowing the smart grid collective to adhere to contracted grid limits.

During hours without capacity constraints, the internal energy price (λ) is expected to align with the contractual grid price per unit of electricity, implying that during these periods, there is no financial incentive for smart grid participants to adjust their energy consumption. However, during the morning peak (08:00 - 10:00), when the capacity restriction is in effect, the internal energy price is expected to rise above the grid price. This price increase is likely to create an economic incentive for participants to optimize their energy consumption within their available flexibility.

The increase in internal energy price is expected to trigger several behavioural responses within the smart grid: Consumers will likely reduce their energy consumption where possible, minimizing unnecessary electricity use. Solar panels are expected to inject all available generated energy into the smart grid, as this becomes financially advantageous due to the elevated energy price. The battery will discharge stored energy into the network to support peak demand and mitigate the impact of the capacity restriction.

Through these interdependent interactions among participants, the smart grid collective is expected to successfully manage energy demand within the contracted capacity limits, demonstrating the effectiveness of flexible energy management strategies under network constraints.

Case Study Results

This section presents and analyses the results of the case study. A comprehensive overview of all findings is provided in Appendix A.

Internal Energy Price and Capacity Constraints

Figure 1 illustrates the development of the internal energy price (λ) within the smart grid over the simulated period. For most of the time horizon, the internal price remains constant, aligning with the predefined contract price of €75 per MWh. This stability suggests that throughout most time steps, the smart grid has sufficient capacity to meet energy demand without the need for additional cost adjustments.

However, a notable deviation occurs at time steps T=8 and T=9, precisely when the capacity constraint is active, reducing the maximum grid capacity from 700 kW to 50 kW. This restriction results in a temporary price increase, indicating that limited supply directly influences the internal market price of electricity within the smart grid.

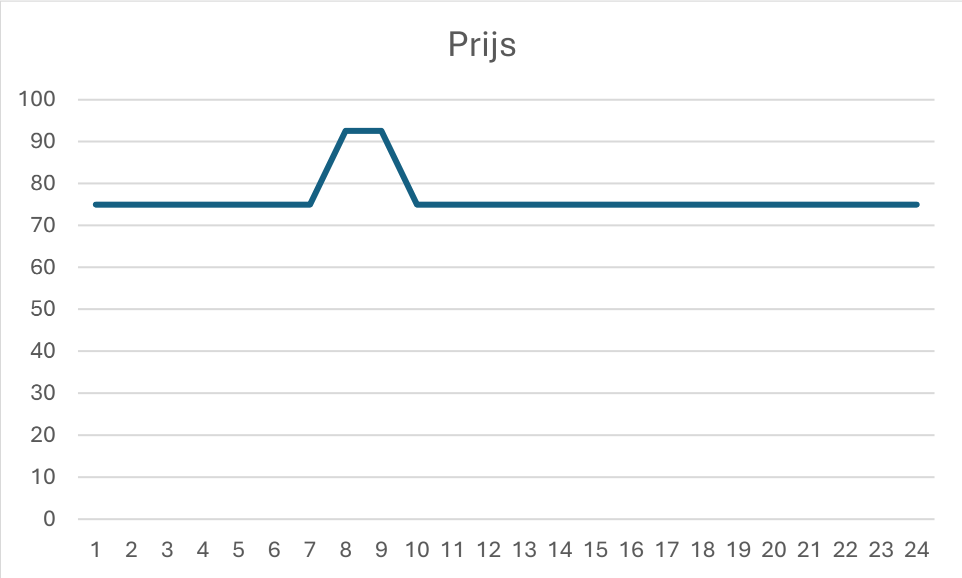


Figure 1: Price Evolution of Internal Energy Price

Demand and Supply Dynamics in the Model

Figure 2 visualizes the interaction between energy demand and supply within the model. The total energy consumption of users is represented by a dark blue cumulative line per time step, demonstrating that energy consumption remains relatively stable throughout the day, with a gradual increase leading to a peak around T=17, followed by a decline.

Additionally, the figure features a light blue line representing battery energy supply. Notably, this line occasionally dips into negative values, indicating that during these periods, the battery is charging rather than discharging. This highlights the dual functionality of the battery as both a consumer and supplier of energy at different time steps.

Throughout all time steps, total energy demand, which includes consumer usage and battery charging demand, is met by a combination of solar PV generation (dark green) and grid supply (orange).

A particularly distinct pattern emerges at T=8 and T=9, when the grid capacity constraint is in effect. During these time steps, grid supply (orange) is visibly reduced, while solar PV availability remains low. Consequently, the battery significantly increases its energy output (light blue peak), confirming its critical role in compensating for reduced grid capacity by bridging the gap between total energy demand and the available energy sources from both the grid and solar PV.

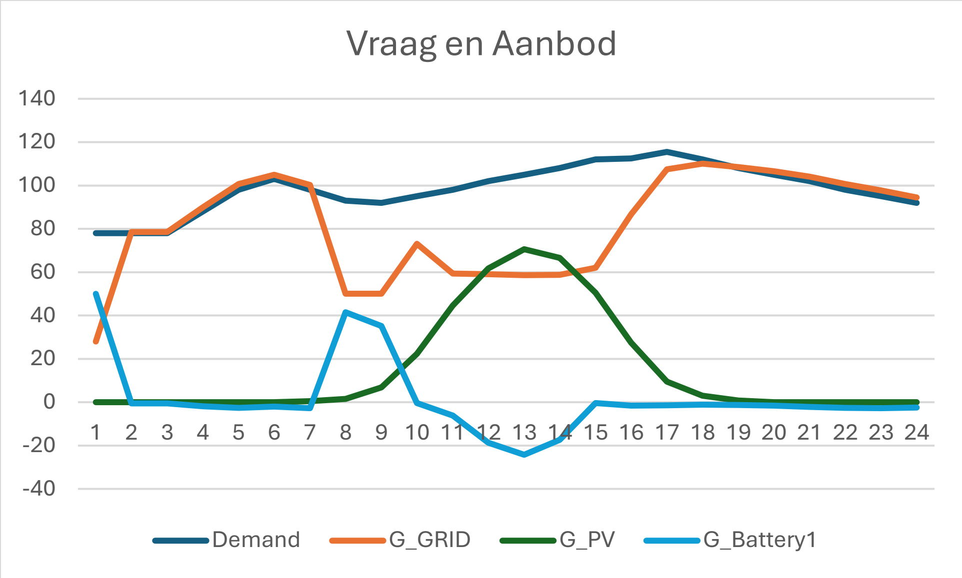


Figure 2: Demand and Supply Dynamics

Comparison Between Hypothesis and Results

The results of the case study are evaluated against the previously formulated hypotheses. The hypothesis predicted that the internal energy price (λ) would remain stable at the predefined contract price of €75 per MWh for most time steps, except during the morning peak (T=8 and T=9), where a deviation was expected due to the capacity constraint. Additionally, it was anticipated that the battery would play an active role in mitigating this restriction and that the interaction between flexible assets and other energy sources would ensure that total energy demand could still be met.

The results align with these expectations. The internal energy price remains stable for most time steps, confirming that the smart grid has sufficient capacity, eliminating the need for price incentives to regulate participant behavior. However, as predicted, T=8 and T=9 show a clear increase in the internal energy price, directly correlating with the contracted grid capacity limitation. This price increase acts as an economic signal, ensuring that the system collectively adjusts its energy usage to comply with the restricted capacity.

The battery's behavior also meets expectations. The results confirm that during the morning peak, the battery supplies a significant portion of the energy demand by discharging stored electricity into the grid. This supports the hypothesis that the battery serves as a buffer, providing the necessary flexibility to offset the grid capacity constraints. Additionally, outside of peak hours, the battery's supply profile shows negative values, indicating that it recharges in preparation for future fluctuations in demand and supply.

The comparison between the model results and the hypothesis confirms that the model, in this simplified form, operates as expected. This validation demonstrates that the model effectively simulates the anticipated behaviors of the energy system in a structured and insightful manner.

In the next chapter, the robustness of the model will be further examined through a series of scenario analyses, introducing extreme variations in both demand and supply. By analyzing the model's response to these disruptions, the study will evaluate whether the underlying assumptions and flexibility mechanisms within the smart grid remain valid under diverse conditions.

Conclusion and Discussion

This case study demonstrates that the simplified smart grid model operates in accordance with expectations and aligns with the formulated hypothesis. The simulation confirms that the model effectively represents the impact of capacity constraints and flexibility options, such as battery storage, providing a structured approach to analyzing energy dynamics within a smart grid.

To further evaluate the robustness of the model, the next chapter will introduce scenario analyses incorporating extreme variations in demand and supply. These analyses will provide deeper insights into the stability and flexibility of the model and assess the extent to which its underlying assumptions hold under diverse conditions. Further refinement and expansion of the model will be necessary to evaluate its applicability in more complex real-world scenarios.

Scenario 1: High Grid Capacity as a Baseline

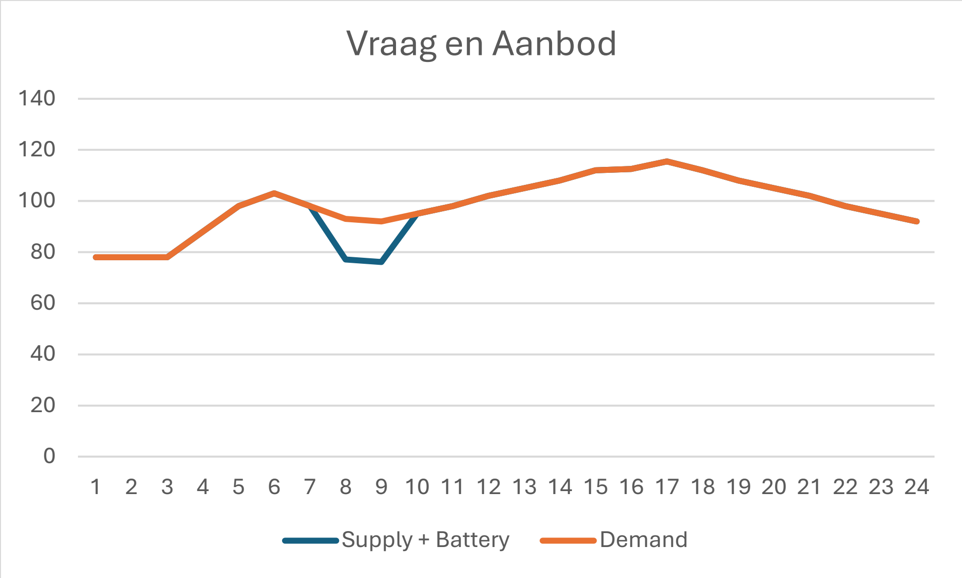
As an initial reference case, this scenario assumes an unrestricted grid capacity, meaning that the local smart grid experiences no limitations due to network constraints. Under these conditions, the hypothesis is that demand and supply will always remain balanced, as there is sufficient grid access to deliver the required energy at any given time step. Additionally, the internal energy price is expected to remain constant, as no grid congestion necessitates price adjustments to influence participant behavior.

The model confirms both hypotheses: the preset energy price remains stable, and supply consistently matches demand. This outcome is logical, as the unrestricted energy availability ensures that all consumers can meet their demand at a fixed price without any market distortions.

Scenario 2: Reduced Battery Capacity (250 kW → 50 kW)

In this scenario, the battery capacity is reduced from 250 kW to 50 kW, limiting its ability to provide flexibility. As a result, during periods of grid constraints, the model fails to maintain a balance between supply and demand, as illustrated in Figure 3. This outcome aligns with expectations, as the previous case study demonstrated that the battery played a critical role in bridging the gap between energy supply and demand.

In the original case, the battery supplied approximately 40 kWh during key time steps to compensate for grid capacity limitations. However, with a reduced storage capacity of 50 kW, it can no longer provide the necessary buffer. Consequently, the model shows that the battery delivers a total of 45 kW over the affected time steps, which corresponds to the maximum available capacity adjusted for storage efficiency losses.

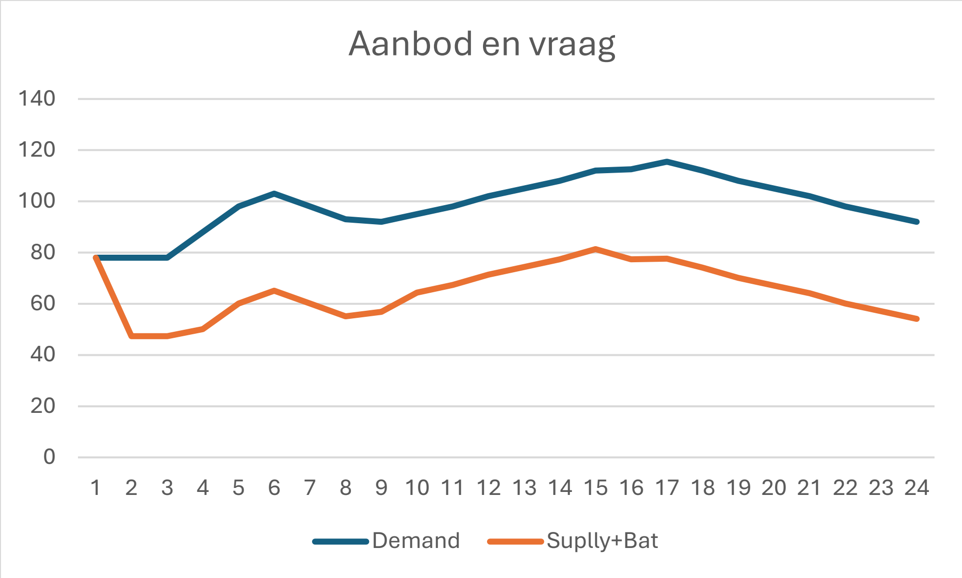


As depicted in Figure 4, the model also records a sharp increase in internal energy prices during periods of capacity limitation. This indicates that equilibrium between supply and demand could not be achieved within the smart grid, leading to extreme price fluctuations as the system attempts to balance itself with limited resources.

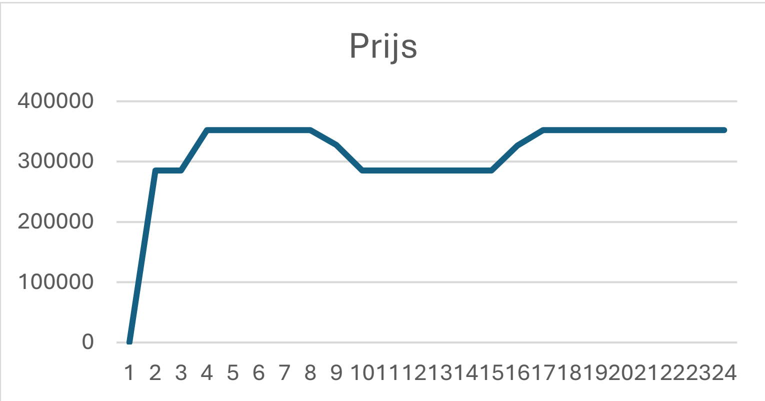
Scenario 3: Continuous Grid Connection Restriction (50 kW Limit)

In this scenario, the grid connection is continuously restricted to 50 kW, rather than being limited only during peak hours. The results show that, with the exception of time step T=1, the model is unable to maintain energy balance at any point. This is consistent with expectations, as the contribution of solar energy in the model is relatively low, making the smart grid highly dependent on external grid supply.

With insufficient grid capacity available, the battery becomes the primary flexibility resource within the system. However, due to its limited storage and discharge capabilities, it cannot fully compensate for the energy shortfall. As a result, the model reveals persistent supply shortages, leading to a deterioration of the energy balance within the grid, as shown in Figure 5.



Additionally, Figure 6 illustrates a steep rise in internal energy prices after T=1. Despite these extreme price fluctuations, the model fails to reach a supply-demand equilibrium, indicating that the pricing mechanisms alone are insufficient to correct for structural shortages. The results suggest that available flexibility options, such as battery storage, are not adequate to fully offset grid capacity limitations, reinforcing the need for additional flexibility solutions within the smart grid.



Appendix C Search scope

Literature review

3.1 Search scope

To identify relevant scientific literature on cost allocation in smart energy networks, a structured search query was conducted in Scopus. This search strategy specifically targets cost distribution methods and pricing mechanisms within decentralized energy systems, including smart grids, microgrids, and energy communities. Given the interdisciplinary nature of this research, the search query was designed to include literature from energy systems, technical optimization, economic models, and mathematical methodologies. To ensure a comprehensive yet precise selection of publications, relevant search terms were combined using Boolean operators (AND/OR) to refine the results effectively.

The literature search was limited to the last five years, ensuring that only recent developments in the field were considered. However, if an article was deemed particularly relevant, publications from up to ten years ago were included. Only scientific journal articles, reports, and books were considered, while conference papers and non-peer-reviewed sources were excluded to maintain the academic rigor of the study.

The search query consists of three main categories, each incorporating synonyms and related terms to capture a broad spectrum of relevant literature. These categories are Cost Allocation and Distribution, Pricing Strategies and Tariff Structures, and Energy Networks and Market Structures. The table below provides an overview of the selected keywords for each category:

Cost Allocation	Pricing Strategies	Energy Networks
"Cost allocation"	"Real-time pricing"	"Smart grid"
"Fair cost sharing"	"Dynamic pricing"	"Microgrid"
"Cost distribution"	"Time-of-use pricing"	"Energy community"
	"Tariff design"	"Decentralized energy market"

Based on these keywords, the Boolean search string used in Scopus was:

("Cost allocation" OR "Fair cost sharing" OR "Cost distribution")
AND ("Real-time pricing" OR "Dynamic pricing" OR "Time-of-use pricing" OR "Tariff design")
AND ("Smart grid" OR "Microgrid" OR "Energy community" OR "Decentralized energy market")

In addition to the structured database search, expert recommendations played an important role in the literature selection process. Articles suggested by research supervisors and field experts, such as Kenneth Bruninx, were included due to their direct relevance to cost allocation and pricing in smart grids. Furthermore, a snowball search method was applied, where relevant articles cited in the initially found literature were analyzed and incorporated into the study. This approach ensured that key studies forming the basis of the field were considered, even if they did not explicitly appear in the keyword-based database search.

3.2 Exclusion Criteria

To ensure the relevance and scientific quality of the selected literature, specific exclusion criteria were applied. These criteria ensure that the reviewed studies directly contribute to the core objectives of this research and provide a robust academic foundation.

First, the search was restricted to peer-reviewed scientific articles, reports, and books, as these sources undergo rigorous academic scrutiny and are therefore methodologically reliable and reproducible. Conference papers, industry white papers, and non-peer-reviewed sources were excluded to maintain the academic integrity of the study.

Additionally, only literature published in English and Dutch was considered. Studies in other languages were excluded to prevent translation bias and interpretation inconsistencies, ensuring conceptual clarity and comparability. To maintain the relevance and applicability of the literature to the evolving energy sector, the search was limited to publications from the last five years (2020–2025). However, if a study was deemed fundamental to the theoretical foundation of cost allocation and pricing mechanisms in smart grids, publications from up to ten years ago (2015–2025) were considered. This approach ensures that both recent advancements and established theoretical principles are accounted for in the research.

Furthermore, the search was refined to the scientific fields of Energy, Engineering, Mathematics, and Business within Scopus. This interdisciplinary scope ensures that the selected literature not only covers the technical aspects of smart grids and energy markets but also incorporates economic perspectives. By maintaining this balance, the research integrates both theoretical insights and practical considerations, ensuring a comprehensive and scientifically grounded tariff model.

3.2 Relevance of the Literature Selection

Searching for literature on cost allocation methods and pricing strategies is essential to addressing the research questions posed in this study. One of the primary objectives is to determine how costs and benefits in a smart grid can be fairly distributed while incentivizing flexible and sustainable behavior. To achieve this, it is necessary to explore existing methods for real-time pricing, tariff structures, and cooperative cost-sharing mechanisms. Furthermore, the literature provides insights into best practices and limitations observed in other decentralized energy projects, allowing for an informed selection of pricing mechanisms for the proposed tariff model. By grounding this research in established theories and empirical findings, the study ensures that its contributions are not only innovative but also aligned with existing knowledge in the field of smart grid economics.

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