

Delft University of Technology

Grid-tariff Mechanism Design for Dynamic Electricity Grid Tariffs

Balancing Congestion Reduction Incentives and User Risks

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Abstract

The Dutch electricity grid is increasingly affected by congestion as electrification and distributed generation increase local peak demand and electricity injection. Dynamic grid tariffs can reflect local network conditions and encourage consumers to adjust electricity use during congested periods. However, these tariffs also introduce risks related to variable and/or volatile charges, consumer complexity, and coordination between electricity-market actor roles. Their implementation therefore requires more than an effective price signal alone.
This research aims to design a grid-tariff mechanism that preserves financial incentives for congestion-responsive behaviour while mitigating the associated risks for grid users. The design must account for differences in household flexibility and the objectives and constraints of network operators, suppliers, and flexibility providers. The central challenge is to balance congestion-related incentives with consumer protection, tariff revenue recovery, and practical implementation requirements.

A design-oriented approach combines a literature review, actor analysis, and stakeholder interviews to establish six quantitative and five qualitative evaluation criteria. Morphological analysis is used to develop alternative mechanisms. Six mechanisms are evaluated against a static tariff: hourly congestion-based pricing applied to all electricity use; dynamic pricing restricted to flexible assets; hourly pricing combined with annual revenue redistribution; a subscription covering a predefined monthly electricity volume; a subscription covering demand up to a predefined capacity; and periodically updated tariff blocks based on expected congestion patterns. Under both subscription mechanisms, electricity use exceeding the subscribed threshold remains exposed to dynamic pricing. A market-based simulation compares the mechanisms using shared hourly network conditions and eight household profiles with different combinations of photovoltaic generation, electric vehicles, heat pumps, and batteries. Qualitative assessment examines implementation complexity, recurring burdens, clarity of purpose, actor roles, and non-discrimination.

The results show that no mechanism performs best across all criteria. Unrestricted hourly pricing closely reflects congestion but combines relatively high tariff volatility with a substantial revenue shortfall relative to the static reference. Restricting dynamic exposure to flexible assets reduces average household costs further, but increases the revenue shortfall and requires asset-specific measurement and administration. The calibrated subscriptions produce revenues closer to the reference, while annual redistribution restores reference revenues by construction. Periodically updated tariff blocks reduce absolute tariff variation while preserving the annual mean of the underlying hourly tariff. This stability comes with lower congestion reflectiveness and a smaller summed tariff-related flexibility benefit. Across mechanisms, household outcomes differ substantially, and protection from dynamic charges does not guarantee a lower annual bill.

A capacity subscription combined with dynamic pricing for exceedance provides the most promising balance under the priorities adopted in this study. It protects demand within the subscribed capacity while retaining financial incentives to reduce exceedance, particularly during congested hours. Under the selected calibration, it combines revenues close to the static reference with the highest sum of tariff-related flexibility benefits across the evaluated assets. The sensitivity analysis shows that higher network demand increases congestion frequency, tariff volatility, and financial exposure for several household profiles. If demand grows without corresponding network expansion, mechanisms that preserve congestion-related incentives while limiting consumer exposure may therefore become increasingly relevant. These advantages come with substantial implementation complexity. Aggregators could help consumers select suitable subscriptions and automate flexible assets, although this contribution has not been quantified. The financial results do not establish realised congestion reduction, since network loading is not recalculated after flexibility activation. The preferred mechanism therefore represents a direction for further development and pilot testing, with its practical value dependent on subscription calibration, household characteristics, and actual network responses.

Contents

List of abbreviations **5**

1 Introduction **6**
1.1 Problem Statement . . . 6
1.2 EmPower project . . . 7
1.3 Research relevance . . . 7
1.4 Research objective and research questions . . . 7
1.4.1 Main research question . . . 8
1.4.2 Subquestion 1 . . . 8
1.4.3 Subquestion 2 . . . 8
1.4.4 Subquestion 3 . . . 8
1.4.5 Subquestion 4 . . . 8
1.5 Design-oriented research approach . . . 9
1.6 Report structure . . . 9

2 Literature review **9**
2.1 Literature selection . . . 9
2.2 Analytical table . . . 10
2.3 Literature analysis . . . 11
2.3.1 Dynamic grid tariffs and congestion management mechanisms . . . 11
2.3.2 Types of grid tariffs . . . 11
2.3.3 Price volatility and risk exposure . . . 14
2.3.4 Modelling approaches for dynamic tariff evaluation . . . 15
2.3.5 Mitigation instruments for price volatility . . . 15
2.3.6 Evaluation criteria . . . 16
2.3.7 Uncertainties for grid users . . . 18
2.3.8 Consumer acceptance and interests . . . 18
2.3.9 Actor roles and market coordination . . . 19
2.4 Research gap and implications for this research . . . 20

3 Methodology **22**
3.1 Subquestion 1 . . . 22
3.2 Subquestion 2 . . . 24
3.3 Subquestion 3 . . . 25
3.4 Subquestion 4 . . . 26
3.5 Data sources . . . 27

4 Actor analysis **28**
4.1 Actor analysis . . . 28
4.2 Problem formulation . . . 28
4.2.1 Actor stakes, constraints, and instruments . . . 28
4.2.2 Synthesis of actor interests and preliminary requirements . . . 29
4.3 Interview insights: empirical actor analysis . . . 31
4.3.1 Interview process . . . 31
4.3.2 Supplier perspective . . . 32
4.3.3 Consumer perspective . . . 32
4.3.4 CSP perspective . . . 32
4.3.5 BRP perspective . . . 33
4.3.6 Aggregator perspective . . . 33
4.4 Key cross-actor insights . . . 33

5 Design criteria **36**
5.1 From actor analysis to design criteria . . . 36
5.2 Defining the criteria set . . . 36
5.3 Overview of criteria . . . 40
5.4 Selection of criteria . . . 41
5.5 Operationalising the criteria . . . 41

5.5.1 Classification by evaluation level . . . 41
5.5.2 Quantitative and qualitative evaluation . . . 43
5.5.3 Defining quantitative indicators and units . . . 44
5.5.4 Defining qualitative criteria metrics . . . 49

6 Conceptual Design of Grid Tariff Mechanisms 53
6.1 Design space . . . 53
6.2 Morphological analysis and design construction . . . 54
6.2.1 Identification of extreme configurations . . . 54
6.2.2 Construction of intermediate configurations . . . 55
6.2.3 Resulting set of representative designs . . . 57
6.3 Conceptual tariff mechanism design . . . 57
6.3.1 Full EmPower . . . 58
6.3.2 Targeted EmPower . . . 59
6.3.3 Ex-post Bonus . . . 59
6.3.4 Flex Volumetric . . . 60
6.3.5 Flex Capacity . . . 60
6.3.6 Adaptive Dynamic Tariff . . . 61
6.3.7 Capacity Steering Contract . . . 62
6.4 Scope of the quantitative evaluation . . . 62

7 Model setup 64
7.1 Motivation . . . 64
7.2 Model objective . . . 64
7.3 Model structure . . . 64
7.4 Model output and application . . . 67
7.5 Input data . . . 67
7.6 Model verification . . . 73
7.6.1 Input and calculation verification . . . 73
7.6.2 Mechanism-specific verification . . . 73
7.6.3 Flexible asset verification . . . 74
7.7 Model validation . . . 75
7.7.1 Conceptual validation . . . 75
7.7.2 Internal validation . . . 75
7.7.3 Extreme values test . . . 77
7.7.4 Sensitivity analysis . . . 79

8 Results 84
8.1 Tariff pattern . . . 84
8.2 Cost exposure . . . 86
8.3 Tariff volatility . . . 89
8.4 Cost recovery . . . 90
8.5 Congestion reflectiveness . . . 91
8.6 Economic incentives . . . 92
8.6.1 Flexibility benefits . . . 92
8.6.2 Congestion reduction incentives . . . 94
8.6.3 Effective tariff burden . . . 95
8.7 Price signal interaction . . . 96
8.8 Results synthesis . . . 97

9 Evaluation 99
9.1 Evaluation approach . . . 99
9.2 Trade-offs between quantitative criteria . . . 99
9.3 Qualitative assessment and implementation implications . . . 101
9.4 Integrated assessment and preferred design . . . 103

10 Discussion 105
10.1 Limitations . . . 105
10.2 Directions for future research . . . 108

11 Conclusion **110**
11.1 Research questions . . . 110
11.1.1 Subquestion 1 . . . 110
11.1.2 Subquestion 2 . . . 110
11.1.3 Subquestion 3 . . . 111
11.1.4 Subquestion 4 . . . 112
11.2 Main conclusion . . . 113
11.3 Practical implementation . . . 114

12 Personal reflection **116**

References **117**

A Analytical table **122**

B Summarised Interview Transcripts **126**

C Consumer interview takeaways **134**

D ADT blocks data **135**

E Calibration of subscription sizes **136**

F Consumer cost exposure tables **140**

G Quantitative assessment tables **142**

H Data: economic incentives criterion **144**

I Qualitative assessment tables **146**

J Consumer electricity imports table **151**

K Tariff statistics **152**

List of abbreviations

Abbreviation	Description
ACM	Authority for Consumers and Markets
ADT	Adaptive Dynamic Tariff
BRP	Balancing Responsible Party
CoV	Coefficient of variation
CP	Consumer profile; CP1–CP8 denote the eight modelled household profiles
CPP	Critical Peak Pricing
CSC	Capacity Steering Contract
CSP	Congestion Service Provider
DSO	Distribution System Operator
DSR	Design Science Research
EV	Electric vehicle
HEMS	Home Energy Management System
HP	Heat pump
ICT	Information and Communication Technology
MSR	Transformer station (Dutch: middenspanningsruimte)
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV	Photovoltaic
RTP	Real-Time Pricing
SoC	State of charge
ToU	Time-of-Use
TSO	Transmission System Operator

Designing Grid-Tariff Mechanisms for Dynamic Grid Tariffs: Balancing Congestion-Reduction Incentives and User Risks

October 5, 2026

1 Introduction

The Dutch electricity system is undergoing a large-scale transition from a centralised electricity system largely powered by fossil fuels towards a system increasingly based on renewable energy sources (Proka, Hisschemöller, & Loorbach, 2018). While this transition is essential for achieving climate targets, it also places increasing pressure on the existing electricity grid. Across the Netherlands, grid capacity is becoming increasingly constrained, resulting in structural network congestion (van Klimaat en Groene Groei, 2025). This congestion requires substantial investments in grid reinforcement and expansion and may negatively affect the Dutch business environment. Currently, approximately 14,000 companies in the Netherlands are waiting for a connection to the electricity grid (van Klimaat en Groene Groei, 2025). At the same time, network capacity is not continuously constrained. On average, approximately 30% of the available grid capacity is utilised, while congestion occurs during specific peak periods (De Bat, 2026). This indicates that improving the utilisation of existing grid capacity may complement physical grid expansion.

However, designing the electricity grid solely around maximum peak demand may not always be the most efficient response to increasingly flexible network use (Mulder, 2020). Instead, financial incentives can be used to allocate scarce network capacity and encourage users to adjust their electricity consumption during congested periods. A promising approach is therefore the introduction of dynamic grid tariffs, in which tariff levels vary according to grid conditions (Mulder, 2020). During periods of high grid utilisation, tariffs increase, creating an incentive for consumers to shift flexible electricity consumption away from congested periods. By promoting a more efficient use of available grid capacity, dynamic grid tariffs may reduce peak demand and lower the need for costly grid reinforcement and expansion (Stute & Kühnbach, 2023).

1.1 Problem Statement

To reduce grid congestion through a more efficient use of the existing grid, Stedin, a Dutch distribution system operator (DSO), initiated the EmPower project. This initiative explores the introduction of dynamic grid tariffs in the electricity market. These tariffs reflect local grid conditions, resulting in higher tariff levels during periods of high grid utilisation and lower tariff levels during periods of lower utilisation. A more elaborate description of the EmPower project is provided in Section 1.2.
However, dynamic grid tariffs may also introduce additional complexity and price volatility for households. Market actors involved in the implementation and operation of these tariffs may face similar challenges, creating broader pressure points across the electricity market. Since access to electricity is essential, these risks need to be carefully considered before such a tariff structure can be implemented on a large scale. At the same time, the requirements and interests of relevant market actors need to be taken into account to support successful market adoption.

This creates a central design challenge for Stedin: the grid-tariff system should maintain a sufficiently strong price signal to incentivise congestion-reducing behaviour, while limiting the associated risks for grid users. Designing such a mechanism is complex because multiple, and potentially conflicting, requirements need to be considered simultaneously (R. J. Hennig, Ribó-Pérez, de Vries, & Tindemans, 2022). This thesis therefore aims to design and evaluate grid-tariff mechanisms that mitigate significant risks for small-scale consumers and addresses the requirements of relevant market actors, while preserving the congestion-reducing price signal of dynamic grid tariffs.

1.2 EmPower project

As mentioned in Section 1.1, the EmPower project was initiated to explore the potential benefits and costs of implementing dynamic grid tariffs for small-scale grid users. Dynamic grid tariffs can take different forms depending on how frequently tariffs change, how they are linked to grid conditions, and whether limits are imposed on tariff levels. Within EmPower, this concept is implemented as an hourly varying grid tariff, in which the tariff level for each hour reflects local grid conditions. To limit exposure to extreme tariff levels, the tariff is subject to a predefined price cap. The aim of this tariff structure is to improve the efficiency, fairness, affordability, and robustness of the future energy system.

By increasing electricity consumption costs during hours of high grid utilisation, the EmPower tariff is intended to reduce grid congestion and, consequently, network costs. Consumers who contribute more to network loading during congestion periods face higher grid tariffs, while consumers who shift their electricity use away from these periods can reduce their tariff costs. This creates a financial incentive for congestion-reducing behaviour and may improve the utilisation of existing grid capacity. At the same time, the price cap limits the maximum tariff exposure faced by participating grid users.

The first stage of EmPower is based on voluntary participation by grid users, including consumers, feed-in parties, and suppliers. Participating parties are exposed to hourly dynamic grid tariffs that reflect congestion caused by both electricity consumption and injection. The tariff can therefore provide flexibility incentives in both directions throughout the day. During hours with consumption-related congestion, particularly during morning and evening peak periods, the tariff increases up to the predefined price cap, creating an incentive to reduce or shift electricity consumption. During hours with injection-related congestion, typically occurring during sunny periods in the late morning and afternoon, the tariff decreases. In these situations, the tariff may even become negative, thereby incentivising additional electricity consumption or a reduction in electricity injection.
This first stage has been implemented in the Vruchtenbuurt, a neighbourhood in The Hague. Households connected to a selected medium-voltage substation (MSR) were given the option to voluntarily participate in the pilot. To investigate the application of dynamic grid tariffs in a different local context, a second pilot is currently being developed in Eemnes.

1.3 Research relevance

Dynamic grid tariffs have the potential to improve the utilisation of existing electricity-grid capacity, but their introduction also affects consumers and electricity-market actors in different ways. These effects depend on actors' roles, responsibilities, flexibility, and ability to respond to tariff signals. A tariff mechanism should therefore not only provide incentives for congestion-reducing behaviour, but also account for the risks and practical requirements of the actors involved.

This research addresses this challenge by identifying actor-specific objectives and constraints and translating them into design criteria for the development and evaluation of alternative grid-tariff mechanisms. By explicitly considering the trade-offs between congestion-related incentives, risk mitigation, and practical implementation, the research aims to support the development of dynamic grid tariffs that are both effective and practically applicable. The findings are therefore relevant for the further development of Stedin's EmPower concept, while also contributing to the broader understanding of how dynamic grid tariffs can be designed in a multi-actor electricity system.

1.4 Research objective and research questions

The objective of this research is to design and evaluate a grid-tariff mechanism that provides effective incentives for grid congestion reduction, while avoiding disproportionate risks for consumers and market parties. Since the aim is not only to analyse existing tariff mechanisms, but also to develop and assess a new mechanism, this research follows a design-oriented approach. This approach enables a structured exploration of possible design options and supports the systematic evaluation of alternative mechanisms.
To guide this research, the following main research question is formulated:

1.4.1 Main research question

What grid-tariff mechanism incorporating dynamic grid tariffs can be designed to provide effective incentives for congestion reduction while mitigating associated risks such as complexity and price volatility for electricity grid users?

This question follows from the central design challenge of this research: dynamic grid tariffs should provide effective incentives for congestion reduction, while avoiding disproportionate risks for consumers and market parties. The research therefore focuses on designing a market mechanism that balances price signal effectiveness with risk mitigation and actor feasibility.
To answer the main research question, four subquestions are formulated:

1.4.2 Subquestion 1

Which actors are impacted by dynamic grid tariffs, and what are their main objectives, stakes, constraints, and instruments?

The first subquestion focuses on exploring the actor landscape affected by dynamic grid tariffs. As electricity systems operate as multi-actor environments, the effectiveness of any proposed mechanism depends on its alignment with the objectives and constraints of the involved actors. Without a clear understanding of these actor interests and requirements, proposed designs risk lacking direction and practical relevance. Therefore, this step aims to identify and structure the key actors and their interests as the foundation for the design process.

1.4.3 Subquestion 2

Which evaluation criteria can be derived from the literature and actor objectives and constraints to guide the design and evaluation of grid-tariff mechanisms?

Building on the actor analysis, the second subquestion focuses on translating actor objectives and constraints into a set of measurable evaluation criteria. These criteria define the performance requirements of the mechanism and specify which problems the design should address. Because actor objectives are not measurable, without these criteria it would not be possible to systematically assess the performance of alternative designs. As the mechanism should satisfy actor objectives as much as possible, the evaluation criteria reflect the overall quality and effectiveness of the design.

1.4.4 Subquestion 3

What grid-tariff mechanisms can be designed to incentivize congestion-reducing behaviour through dynamic grid tariffs while mitigating the risks for grid users identified through the literature and actor analyses?

The third subquestion focuses on the design of potential solutions. It aims to explore and construct plausible grid-tariff mechanisms that address the identified problem. This step forms the core of the design-oriented approach, as it generates alternative configurations that balance the trade-off between price signal effectiveness and risk exposure for grid users. The risks referred to are identified through the literature and actor analyses presented in Chapters 2 and 4. These analyses determine which risks associated with dynamic grid tariffs should be addressed in the design of the tariff mechanism. By exploring multiple design options, the research identifies mechanisms that are theoretically sound and practically relevant.

1.4.5 Subquestion 4

How do alternative grid-tariff mechanisms perform for different household profiles and electricity market actors, based on the evaluation criteria defined in Step 2?

The fourth subquestion focuses on evaluating the performance of the designed mechanisms. Using the evaluation criteria defined in the previous step, alternative designs are assessed in terms of their ability to meet the defined objectives. This step aims to determine which mechanisms perform best across different consumer profiles and criteria. The results of this evaluation provide the basis for answering the main research question.

Together, these subquestions structure the research process from understanding the problem context, to defining performance criteria, designing solutions, and evaluating their effectiveness.

1.5 Design-oriented research approach

Because the objective of this research is not only to analyse existing tariff mechanisms, but also to develop and evaluate alternative tariff mechanisms, a Design Science Research (DSR) approach is applied. DSR consists of six iterative steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication (Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). This approach is suitable for the present research because the proposed tariff mechanism must balance multiple and potentially conflicting objectives, constraints, and requirements within the electricity system.

Within this research, the actor analysis and literature review support the identification of the problem and the definition of design objectives. These objectives are translated into design criteria, after which alternative grid-tariff mechanisms are developed through a structured design process. The mechanisms are subsequently demonstrated and evaluated using a simulation model and qualitative assessment. In this way, DSR provides an overarching structure that connects the problem analysis, mechanism design, and evaluation. The research subquestions are formulated to collectively follow these stages and ultimately support the design of a grid-tariff mechanism that provides congestion-reducing incentives while mitigating associated risks for grid users.

1.6 Report structure

This thesis follows the Design Science Research approach introduced in Section 1.5. Chapter 2 presents the literature review, providing the theoretical foundation on dynamic grid tariffs, relevant market actors, tariff evaluation, and mechanisms for mitigating risks associated with dynamic pricing. Chapter 3 describes the research methodology. Chapters 4 and 5 analyse the relevant actors and translate their objectives, constraints, and requirements into design criteria. Chapter 6 uses these criteria to structure the design space and develop alternative grid tariff mechanisms. Chapter 7 presents the simulation model used to support the quantitative evaluation of these mechanisms. Chapter 8 presents the simulation results, after which Chapter 9 evaluates the alternative mechanisms against the quantitative and qualitative criteria. Chapter 10 discusses the findings, limitations, and directions for future research. Chapter 11 answers the research questions, presents the main conclusions, and discusses implications for practical implementation. Finally, Chapter 12 provides a personal reflection on the research process.

2 Literature review

This literature review is performed to identify and collect existing knowledge on the design of grid tariffs. While the pilots performed by Stedin provide insights into the effects of hourly dynamic grid tariffs on consumers, previous academic research has also researched the potential of grid tariffs. This literature provides the state-of-the-art knowledge on grid tariffs. By performing a literature review, existing knowledge is collected. This knowledge forms the foundation for the solution to the problem. Therefore, a literature review is performed in this section.

2.1 Literature selection

To select relevant literature for the literature analysis, studies were identified through database searches and subsequently screened for relevance. The selection process is summarised in the PRISMA flow

diagram shown in Figure 1.

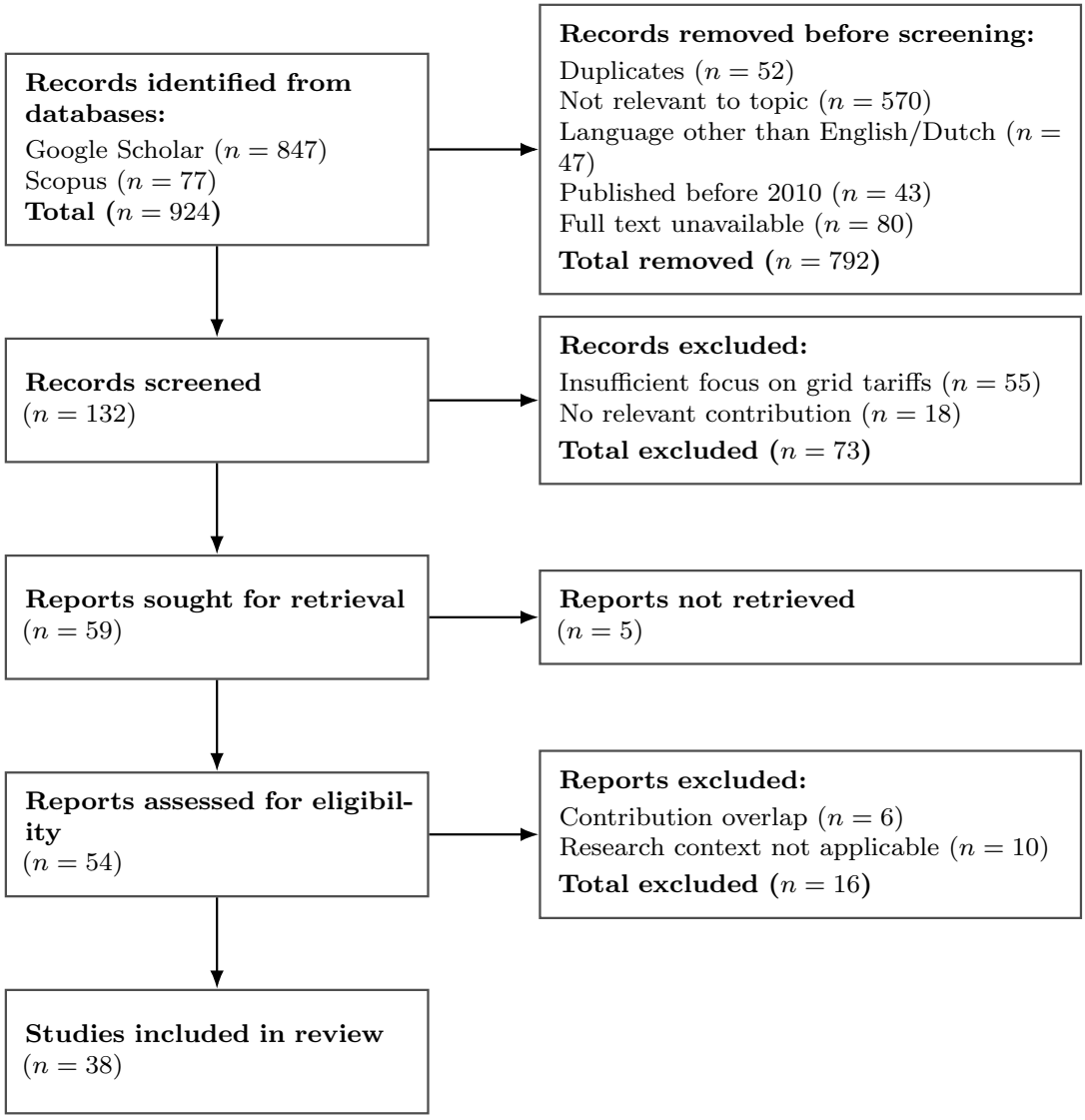

Figure 1: PRISMA flow diagram for literature selection

The selection process consisted of several consecutive screening steps. Studies published before 2010 were excluded because the technological and institutional context of dynamic electricity tariffs has changed considerably in recent years. Developments such as smart metering, distributed energy resources, household flexibility, and new market roles have substantially altered the conditions under which dynamic tariffs are implemented. More recent studies were therefore considered more representative of the current electricity-market context.

Studies were also excluded when the full text could not be accessed. In several cases, the articles were only available through journal subscriptions or other restricted-access platforms. During the subsequent screening stages, studies were excluded when they focused insufficiently on grid tariffs, did not provide a relevant contribution to the research problem, substantially overlapped with already selected literature, or were based on a research context that was not sufficiently applicable to this study.

2.2 Analytical table

The analytical table formed the basis for the literature analysis by enabling a structured comparison of the reviewed studies and supporting the identification of similarities, differences, and recurring themes.

The complete analytical table is provided in Appendix A.

To structure this comparison, the table consists of seven columns: year, author, theme, methodology, mechanism or concept, key contribution, and limitation. The year and author identify each study, while the theme categorises its main focus. The methodology describes the analytical approach applied in the study, and the mechanism or concept indicates the tariff, market mechanism, or related concept examined. The key contribution summarises the main insight of the study that is relevant to this research, whereas the limitation places the findings in context and helps identify remaining knowledge gaps.

The most frequently recurring themes in the reviewed literature are tariff design, risk mitigation, and network modelling. The applied methodologies vary considerably, ranging from machine-learning and optimisation-based modelling approaches to literature reviews and qualitative analyses. These themes, methodological differences, and the main findings of the reviewed studies are discussed further in the literature analysis.

2.3 Literature analysis

To look at the entirety of the problem situation, dynamic grid tariffs are not an end in themselves, but a mean to support Stedin's core public task: ensuring a secure, reliable, affordable and future-proof electricity system. Congestion management is one of the key challenges that must be addressed in fulfilling that task.

2.3.1 Dynamic grid tariffs and congestion management mechanisms

Congestion management consists of more elements next to grid tariffs alone, it requires a toolbox of complementary instruments. To position dynamic grid tariffs within the broader solutions space, alternative congestion management mechanisms are reviewed. According to Alavijeh (2023), there are alternative complementary mechanisms like Local Flexibility Markets (LFMs), Local Energy Markets (LEMs), or bilateral flexibility agreements. Local Flexibility Markets are platforms where DSOs, aggregators and suppliers realise short-term demand reductions or injections from local assets (e.g., EVs, heat pumps, batteries) to relieve specific elements of grid constraints. Local Energy Markets are community- or regional-scale marketplaces that enable decentralized trading and coordinated planning of local generation, storage, and demand. The primary aim of LEMs is to optimize local self-consumption and reduce upstream grid use. Congestion relief can also be a benefit when clearly communicated with the DSO. Bilateral contracts are made between the DSO (or another system party) and a flexibility provider, specifying volumes and generation conditions.

Alavijeh (2023) explains that these different types of congestion management mechanisms can complement dynamic grid tariffs in reducing congestion. While these mechanisms are relevant for congestion management, the problem of Stedin mainly lies with dynamic grid tariffs. Therefore, this study zooms in on the design of grid tariffs. This does not mean that this study focuses on one tariff type, as grid tariffs exist in several different forms. The next section will look into these types.

2.3.2 Types of grid tariffs

In academic literature, several types of grid tariffs are described. An important aspect is on which aspect of electricity demand the tariffs are charged for. Across the literature, three main components of network tariffs are commonly distinguished: fixed charges (€/period), volumetric charges (€/kWh), and capacity charges (€/kW) (Wang et al., 2023). Fixed charges, also called 'Lump-sum payments', are not charged based on the electricity consumption, while volumetric charges are based on the energy demand (Winzer & Hensler-Ludwig, 2024). On the other hand, capacity charges are based on peak demand: how high are the power peaks? The differences between these types can be explained by using a metaphor about a water tap: a lump-sum tariff can be compared to paying a fixed monthly fee for water, regardless of how much is used. A volumetric tariff corresponds to paying per litre consumed, directly linking costs to usage. A capacity-based tariff, however, resembles paying for the maximum flow rate of the water connection, where costs are determined by the size of the maximum flow rate of water, rather than total consumption. Each type brings different effects for consumers, which are

further explained in the following paragraph.

In addition to the charged aspect of usage, another distinction is identified by Schittekatte et al. (2024). They describe the difference between static and dynamic tariffs:

Static tariffs

Static tariffs can vary over time, but do not respond to grid conditions.

- Lump-sum payments: static periodically fees (e.g. the current system in the Netherlands) (Enexis, n.d.).
  In the Dutch system, network tariffs are largely predetermined and consist of fixed charges based on the type and capacity of the grid connection. These tariffs are billed periodically (typically once per year), and therefore remain constant within that period. This causes the tariff-based consumption costs for consumers to be independent of actual grid usage patterns or peak load moments. As a result, consumers face stable and predictable network costs, but receive little to no incentive to shift consumption in time.

- Time-of-Use (ToU):
  The ToU mechanism defines different tariff levels for predefined time blocks, such as seasons, types of days (e.g. weekdays versus weekends), or peak and off-peak hours (Schittekatte, Mallapragada, Joskow, & Schmalensee, 2024). These tariffs are typically based on historical consumption patterns and are communicated well in advance (e.g. on a yearly basis). Under ToU pricing, consumers are incentivised to shift or reduce their demand to lower-cost periods, while still being protected from unexpected price volatility. This approach is widely applied in Europe, with large-scale implementation in countries such as France, Spain, and the United Kingdom, as well as in the Nordic countries (Norway, Sweden, Finland, and Denmark) (Energy, n.d.).

Because these tariffs are predefined, they do not actively reflect grid conditions. To increase the tariff reflectivity, dynamic tariff types have been designed. These tariffs respond to grid congestions.

Dynamic tariffs

Hennig et al. (2022) describe that dynamic grid tariffs can be used as an instrument to reduce grid congestion. Because dynamic grid tariffs adapt to the grid pressure, consumers are incentivised to shift their demand away from peak hours. By decreasing demand during peak-hours, the network can be utilised more efficiently, leading to less needed grid expansions. The key difference between static and dynamic tariffs is that dynamic tariffs actively respond to grid conditions. Schittekatte et al. (2024), Dutschke & Paetz (2013), and Boontagool & Wirasanti (2024) identify three types of dynamic pricing:

- Critical peak pricing (CPP).
  CPP is designed to reduce consumption during periods of heavy congestion (Schittekatte et al., 2024). The system operator announces the CPP periods on short notice, for example day-ahead. During these periods, consumers enrolled in CPP contracts are exposed to high grid tariffs that typically last for a couple of hours.

- Real-time pricing (RTP)
  RTP provides hourly or more frequent electricity prices. The prices reflect the current market conditions regarding supply, demand and congestion (Dütschke & Paetz, 2013). These prices can vary but are communicated to consumers at least 1 hour beforehand. This transparency is essential to reach the goal of RTP: shifting flexible demand away from peak hour. Hinchberger et al. (2024) highlight an advantage of RTP: it aligns the consumer prices with the marginal costs of providing electricity. Therefore, it incentivises consumers to adjust their behaviour to the system's needs. By aligning consumer behaviour with the needs of the system, the grid is used more efficiently. Hinchberger et al. (2024) also find that the reduction of required grid investments leads to an increase in social welfare. Another possible aspect of RTP is nodal pricing, which means that electricity prices differ between congested zones and zones with less congestion. According to Neuhoff (2025), nodal pricing could improve the accuracy of the network tariffs. However, Neuhoff et al. (2025) also note that implementing Locational Marginal Pricing (LMP) would require a large-scale reorganisation of the energy system, making it a relatively heavy and

complex mechanism.
RTP has been implemented in multiple European countries, with Norway, Sweden, Finland, and Denmark as leading countries (Energy, n.d.).

- Adaptive Dynamic Tariffs
  Adaptive Dynamic Tariffs use expected demand or congestion patterns to determine tariff periods that remain fixed for a limited time horizon, such as a week or a month (Boontagool & Wirasanti, 2024). First, the expected electricity demand is estimated for each hour of the day. Based on this profile, periods in which congestion is expected are identified and assigned a higher tariff, while lower tariffs apply during periods with lower expected grid loading. These tariff blocks remain constant within the selected period and are periodically updated when expected demand or congestion patterns change. As a result, Adaptive Dynamic Tariffs are more responsive to changing grid conditions than conventional Time-of-Use tariffs, while remaining more stable and predictable than fully real-time pricing.

In addition to these three types of tariffs, other types of dynamic pricing have been designed to mitigate certain user risks while also incentivizing demand shift through price signals.
Fabra et al. (2022) introduce reliability options, where regulators engage in contracts with market parties applying a certain strike price. When market prices exceed this level, consumers are shielded from extreme scarcity prices through an effective price cap, while generators receive compensation for delivering during periods when electricity is scarce. Batlle et al. (2022), on the other hand, focuses on affordability measures aimed at preventing excessive consumer bills without reducing the incentive to shift demand during periods of congestion. He proposes to apply bill caps only when prices increase heavily. This ensures that consumers are protected while still having the incentive to reduce consumption. Another proposal by Batlle et al. (2022) is to tax excess revenues of power suppliers above a defined threshold, generating revenues that can be redistributed to lower the bills of vulnerable consumers.

While both of these two types were originally designed for electricity prices, their functionality can also be applied to dynamic grid tariffs. Electricity prices are mainly volumetric, meaning that users pay a price per kWh (€/kWh). This price flows from the supply and demand: the price drops when supply is high and demand is low, and the other way around. Dynamic grid tariffs have the same unit, and the same logic: when the grid is full, the price becomes higher. In electricity markets, prices reflect scarcity of generation or supply, whereas dynamic grid tariffs reflect scarcity of network capacity. Despite these differences in context, both mechanisms aim to influence consumer behaviour through price signals. As a result, design concepts such as price caps, strike prices, or revenue redistribution can be adapted to the context of grid tariffs to mitigate price volatility while preserving incentives for demand response. Therefore, this research does not directly copy these mechanisms, but rather adapts their core principles to the specific characteristics of regulated distribution tariffs.

While static- and volumetric tariffs and local market structures have different characteristics, previous research has proven that combining these types can lead to improvements in performance. Such mechanisms are defined as hybrid mechanisms.

Hybrid mechanisms

Hybrid mechanisms combine dynamic and static tariffs with local market structures. Ormeno et al. (2024) introduce a two-layer structure in which dynamic network tariffs provide the primary signal, while any remaining congestion is addressed through a local flexibility market. Shen et al. (2022) propose an aggregator-based approach where aggregators can spread flexibility across consumers, preventing extreme prices by combining scheduled reprofiling products (SRP) with dynamic tariffs. Scheduled reprofiling products are incentive signals, meaning that offering flexibility is rewarded with monetary benefits. These hybrid solutions show how tariff-based incentives can be improved by coordination mechanisms to address congestion more efficiently while reducing individual user exposure to volatility.

In addition to volumetric grid tariffs, capacity-based tariff mechanisms have been designed (R. Hennig, Jonker, Tindemans, & de Vries, 2020). While volumetric tariffs are charged per unit of energy consumed (€/kWh), capacity-based tariffs are based on the maximum power demand (kW). The primary objective of capacity-based tariffs is to target peak demand specifically, rather than influencing total

energy consumption.

Capacity-based grid tariff

Hennig et al. (2020) define the mechanism called 'capacity subscription', also called a 'dynamic capacity contract'. In this mechanism, consumers subscribe to a certain capacity level that they may use at any moment without facing additional charges. The capacity limit would only be applied during congestion hours. When a user exceeds this subscribed level during these hours, there are two possible consequences: either an additional fee is charged for each excess kW, or the user is automatically placed in a higher subscription level for the next settlement period. In terms of performance, capacity subscription systems are relatively complex to implement but are more cost-reflective compared to fixed charges. In addition, they provide consumers with predictable information on their usable capacity. They are also effective at reducing the risk of transformer overloading by preventing collective high peak loads. A related variant is the bandwidth tariff (van der Holst et al., 2023), which allows consumers to operate within an approved bandwidth. Exceeding this bandwidth results in additional fees.

Altogether, three types of mechanisms have been identified: dynamic/static grid tariffs, hybrid mechanisms, and capacity mechanisms. Table 1 shows an overview of the different tariff mechanisms that have been found.

Table 1: Overview of grid tariff structures

Tariff structure	**Short description**
Fixed / periodic tariffs	Tariffs remain constant over a predefined period and do not vary with short-term grid conditions.
Time-of-Use (ToU)	Predefined tariff levels apply during fixed time blocks, such as peak and off-peak periods.
Real-Time Pricing (RTP)	Tariffs vary frequently, for example hourly, in response to changing grid conditions.
Critical Peak Pricing (CPP)	Higher tariffs are applied during a limited number of announced critical peak periods.
Adaptive Dynamic Tariffs (ADT)	Tariff levels or time blocks are periodically adapted in response to changing grid conditions.
Capacity subscription	Consumers subscribe to a predefined capacity level for a fixed periodic charge.
Bandwidth tariffs	Consumers operate within predefined capacity boundaries, with additional charges or conditions when these boundaries are exceeded.

These alternative designs differ in terms of predictability, complexity, and the level of risk exposure they impose on grid users. This raises the question of how to design a tariff that provides an effective price signal without exposing grid users to excessive uncertainty. Berenschot (2024) stresses that more dynamic tariffs can potentially increase both price unpredictability and price uncertainty, exposing grid users to significant risks associated with tariff volatility.

2.3.3 Price volatility and risk exposure

Price volatility means that the grid tariff fluctuates very heavily, leading to sudden price spikes or drops. Roozbehani et al. (2012) explain these price spikes through a closed feedback loop: supply responds to demand, while demand also responds to the supply. This feedback loop can cause heavy price spikes. Therefore, Roozbehani et al. (2012) argue that mitigation methods are needed. Sudden price spikes form a danger for several types of grid users: they create a barrier for large-scale adoption. Matisoff et al. (2020) find that for small-scale consumers, a large share of demand is non-flexible, for example refrigeration or lighting. Companies often carry out continuous processes, which cannot be stopped at any time in response to rising grid tariffs. Therefore, this volatility forms a barrier for large-scale citizen/industrial participation. To overcome this barrier, Lee (2022) finds that electricity consumers need a price instrument which enables them to mitigate their price risk caused by price volatility.

Given the potential risks of dynamic grid tariffs for consumers, previous studies have applied modelling approaches to assess their financial impacts and consumers' ability to respond to dynamic tariff signals.

2.3.4 Modelling approaches for dynamic tariff evaluation

Previous research applies different modelling approaches to evaluate dynamic electricity tariffs. The appropriate approach depends primarily on the objective of the analysis. Power-flow and system optimisation models focus on physical network conditions, such as voltage levels and power flows (Balamurugan & Srinivasan, 2011; Jha et al., 2023). When the objective is instead to evaluate the economic response of consumers to tariff signals, simulation and optimisation approaches can be used to combine time-varying tariffs with electricity demand and flexibility. Such approaches have been applied to evaluate, among others, capacity subscriptions, adaptive tariffs and dynamic pricing mechanisms (R. Hennig et al., 2020; Boontagool & Wirasanti, 2024; Blaschke, 2022; Miletić et al., 2022a).

An important consideration in tariff modelling is consumer heterogeneity. The ability of households to respond to dynamic tariffs depends on their electricity consumption and the energy assets available to them. Previous studies therefore distinguish between consumers based on technologies such as photovoltaic (PV) systems, electric vehicles (EVs), heat pumps and battery storage. Flexible and automated households generally have greater opportunities to respond to dynamic price signals, while households with limited flexibility may face greater financial exposure (Miletić et al., 2022b; Andreas Gunkel et al., 2023; Matisoff et al., 2020). As these technologies provide different forms and levels of flexibility, the use of multiple consumer archetypes allows the distributional effects of dynamic grid tariffs to be evaluated more explicitly (Blaschke, 2022; Andreas Gunkel et al., 2023; Miletić et al., 2022b; Sironja et al., 2025).

Consumer flexibility can be represented through optimisation of flexible assets. Battery storage is particularly suitable for this purpose, as charging and discharging can be shifted in time in response to changing prices. Existing approaches range from detailed system-level optimisation, incorporating network and technical constraints (Mehrjerdi & Hemmati, 2019), to household-level optimisation of PV-battery systems (Hesse et al., 2017). For dynamic pricing, Selim et al. (2023) formulate battery scheduling as a cost-minimisation problem in which charging and discharging decisions respond to time-dependent electricity prices while accounting for storage capacity, power limits and efficiency losses.

Overall, the literature indicates that modelling approaches can be used to assess how exposure to dynamic tariffs differs between consumers depending on their demand characteristics and available flexibility. Representing multiple consumer archetypes and explicitly modelling flexible assets is therefore important when evaluating both the risks associated with dynamic tariffs and the extent to which consumers can respond to them. These insights provide a methodological basis for the evaluation model developed in this research.

2.3.5 Mitigation instruments for price volatility

To mitigate the price risk of price volatility, several instruments are applicable with small-scale consumers.

Four types of instruments have been identified by Miletic et al. (2022), Hennig et al. (2020), and Sironja et al. (2025).

- Technical flexibility instruments
  Technical flexibility can reduce consumers' exposure to price volatility by increasing their ability to adjust electricity consumption or generation in response to changing tariff signals. Flexible technologies such as electric vehicles, heat pumps, and home batteries allow electricity use to be shifted away from periods with high tariffs. Households with access to such flexibility can therefore reduce the financial impact of dynamic pricing more effectively than households with largely inflexible demand (Miletić et al., 2022a). Automation through energy management systems can further support this response by coordinating flexible assets without requiring continuous active decisions from consumers. Technical flexibility therefore mitigates price risk by increasing the ability to respond to volatile tariffs, rather than by limiting the tariff variation itself.

- Tariff-based risk-mitigation instruments
  Price volatility can also be mitigated through adjustments to the tariff structure itself. Pototschnig et al. (2022) propose combining a fixed price for a predefined base quantity with real-time pricing for deviations from this quantity. Such a structure protects part of the consumer's electricity use from short-term price fluctuations, while maintaining a dynamic price signal for additional consumption. Other options include price caps and floors, which limit the maximum or minimum tariff level and thereby reduce exposure to extreme price fluctuations. Capacity-based mechanisms can provide a similar form of protection by allowing consumers to use a predefined level of capacity under more stable tariff conditions, while applying additional charges when this level is exceeded (R. Hennig et al., 2020). These instruments therefore mitigate price risk by limiting the extent to which consumers are exposed to volatile tariff signals, although this protection may also weaken the strength of the congestion-related price signal.

- Information instruments
  Information instruments can mitigate the risks associated with price volatility by improving users' ability to anticipate and respond to changing tariff signals. Accessible data platforms can provide consumers and market parties with accurate and timely information on electricity prices, grid tariffs, and relevant system conditions. Sironja et al. (2025) show that access to such information can support coordinated adjustment of electricity demand and supply within collective energy-use groups. Better information therefore enables users to plan and optimise their electricity use more effectively and can reduce their exposure to high-price periods. Information instruments do not reduce tariff volatility itself, but reduce the uncertainty associated with volatile tariffs by making price signals more transparent and actionable.

- Coordination and aggregation instruments
  Coordination and aggregation instruments can mitigate price risk by managing electricity consumption, generation, and flexibility collectively rather than at the level of individual consumers. Sironja et al. (2025) describe energy hubs as local networks in which households and/or companies coordinate and share electricity resources such as generation and storage. By combining electricity demand, generation, and flexibility across multiple users, individual differences can partly offset each other and the group can respond more effectively to changing price signals. Aggregators can provide a similar function by coordinating flexible assets across multiple consumers and optimising their operation on behalf of the group. These instruments therefore reduce individual exposure to price volatility through collective optimisation and risk sharing, without necessarily reducing the volatility of the tariff itself.

While these instruments can mitigate risks associated with dynamic tariffs, their effectiveness and broader impacts differ across consumers and market actors. Assessing these effects therefore requires a structured evaluation framework that captures both the benefits and potential drawbacks of alternative tariff designs.

2.3.6 Evaluation criteria

Grid tariff designs affect the involved actors in multiple ways. Although their financial impact is an important consideration, tariff mechanisms must also be evaluated in terms of their technical, social, and regulatory implications. Consequently, the evaluation of grid tariff designs requires a multidimensional perspective.

Christensen, Ma and Jorgensen (2021) distinguish four dimensions for evaluating tariff designs: technical, economic, social, and regulatory feasibility. Technical feasibility concerns the extent to which a tariff mechanism can be practically implemented and adopted by the involved actors. Economic feasibility considers the financial implications of the mechanism and whether these result in acceptable economic outcomes. Social feasibility relates to user convenience and the effort required from actors to understand and respond to the tariff structure. Finally, regulatory feasibility concerns the compatibility of a tariff design with the applicable legal and regulatory framework (Christensen, Ma, & Jørgensen, 2021). Together, these dimensions provide a broad structure for considering the different types of impacts associated with tariff design.

Whereas Christensen et al. (2021) provide broad evaluation dimensions, Hennig et al. (2022) formulate more specific objectives for the evaluation of distribution network tariffs. They identify five main objectives: cost recovery, cost reflectiveness, non-discrimination, cost efficiency, and simplicity. Cost recovery concerns the ability of tariffs to recover network costs through sufficiently stable revenues. Cost reflectiveness considers whether tariff charges correspond to the network costs caused by users. Non-discrimination concerns the equal treatment of users exhibiting comparable behaviour. Cost efficiency relates to the costs associated with implementing and operating the tariff mechanism, while simplicity addresses the complexity of the tariff design, including its temporal variation and comprehensibility (R. J. Hennig et al., 2022).
Abdelmotteleb et al. (2017) provide an additional perspective by evaluating tariff designs according to four criteria: network cost recovery, savings in required network reinforcements, efficient consumer response, and recognition of side-effects on consumers . While cost recovery is also mentioned by Hennig et al. (2022), the other three complement their set of criteria. The criterion 'savings in required network investments' measures the financial benefits of reducing the amount of grid expansions due to the space freed by the tariff design. Efficient consumer response refers to the ability of a tariff to provide consumers with appropriate economic signals to adapt their electricity consumption in a way that contributes to more efficient network use. In the context of dynamic grid tariffs, this implies incentivising consumers to shift or reduce consumption during periods of high network utilisation, thereby contributing to congestion reduction.
Recognition of side-effects on consumers concerns the unintended consequences that a tariff design may have for consumers. Although stronger price signals can encourage efficient network use, they may also increase consumers' electricity costs or disproportionately affect consumers who have limited ability to adjust their consumption. Tariff evaluation should therefore consider these adverse consumer impacts alongside the intended network benefits.

Wang et al. (2023) complement these evaluation frameworks by highlighting several additional principles that are particularly relevant for dynamic network tariffs. First, they identify the widespread availability of smart metering as an important prerequisite, since dynamic tariffs depend on sufficiently detailed and timely consumption data. In addition, they identify additivity, feasibility of practical implementation, and intelligibility as relevant principles for tariff design. Additivity refers to the extent to which the distribution tariff is compatible with existing and foreseeable pricing structures of suppliers and other market actors. This is particularly relevant for dynamic grid tariffs, as consumers may simultaneously respond to electricity prices and grid tariff signals. Feasibility of practical implementation concerns whether the tariff can be implemented cost-effectively using available or foreseeable metering and ICT infrastructure, without communication requirements becoming a barrier. Finally, intelligibility concerns whether consumers understand how their tariff costs are determined and how their behaviour can affect these costs (Wang et al., 2023).

Together, these approaches are complementary. Christensen et al. (2021) provide an overarching structure for classifying the effects of tariff mechanisms, whereas Hennig et al. (2022), Abdelmotteleb et al. (2017) provide more specific objectives through which tariff performance can be assessed. Their findings also show that more dynamic and cost-reflective tariffs may strengthen network-related incentives, while simultaneously introducing trade-offs related to complexity, consumer impacts, and the allocation of network costs. Wang et al. (2023) further complement these frameworks by emphasising the interaction with other price structures, practical implementation, consumer intelligibility, and the technical prerequisites required for dynamic tariff implementation. Together, these studies provide the literature-based foundation for developing the design criteria used in this research.

At the same time, these studies highlight that improvements in one aspect of tariff design can create disadvantages elsewhere. Increasing cost reflectiveness, for example, may require greater temporal differentiation and thereby increase complexity or uncertainty for grid users. Similarly, stronger incentives for efficient consumer response may lead to differences in cost exposure between consumers with different levels of flexibility. The evaluation of dynamic grid tariffs therefore requires explicit consideration of such trade-offs. These literature-based evaluation principles are combined with the actor-specific requirements identified in the actor analysis to develop the design criteria in Chapter 5.

2.3.7 Uncertainties for grid users

The price volatility described in section 2.3.3 creates uncertainties for grid users, because grid tariffs get increasingly harder to predict, according to Muğaloğlu et al. (2026). While the four mitigation instruments described in section 2.3.5 offer some possibility for risk mitigation, uncertainties remain. Blaschke (2022) found that these uncertainties pose problems for grid users because they desire financial stability, avoidance of lifestyle disruption and investment certainty. In addition, Miletic (2022) highlighted that those uncertainties also affect the possibilities for imbalance management, which is also an important aspect of the electricity market. Goedeburge and Hennig (2022) highlight that the time horizon over which tariffs are communicated is an important factor for the usability for grid users. The earlier tariffs are published, the greater the opportunity for households and companies to adjust and schedule their consumption and generation. Consequently, the publication horizon of dynamic tariffs is an important element of the tariff structure to assess uncertainty and users' ability to act on price signals.

In addition to creating opportunities for grid users, it is essential that these parties demonstrate a sufficient level of acceptance of the grid tariffs they are exposed to. If grid users are unwilling to cooperate or respond to tariff signals, the mechanism will most likely not achieve its intended effects, such as peak demand reduction.

A key factor in the acceptance of grid tariff systems is the response of the consumers who are subject to these tariffs.

2.3.8 Consumer acceptance and interests

Bjarghov (2022) argues that consumer acceptance is a key condition for the successful implementation of dynamic tariffs (Bjarghov, Farahmand, & Korpås, 2022). Even when tariffs are economically efficient or cost-reflective, they may be perceived as unfair, particularly if they result in higher costs for consumer groups with limited ability to adjust their consumption patterns.
Boom & Schwenen (2021) and Dütschke & Paetz (2013) identify several recurring consumer interests regarding dynamic electricity tariffs. Consumers generally prefer a tariff mechanism that:

- is easy to understand;
- limits electricity costs and exposure to unexpected bill increases;
- has a clearly identifiable purpose;
- requires few additional actions from consumers. (Boom & Schwenen, 2021; Dütschke & Paetz, 2013)

These consumer preferences are consistent with the principle of intelligibility identified by Wang et al. (2023), which refers to consumers' ability to understand how tariff costs are determined and how their behaviour can influence these costs (Wang et al., 2023). This further highlights the importance of transparent and comprehensible tariff structures for consumer acceptance. Therefore, a successful tariff design requires not only economic efficiency but also social acceptability. This can be achieved through transparent communication, gradual implementation, and the inclusion of protection mechanisms for vulnerable or inflexible consumers.

One straightforward way to reduce these uncertainties is to reduce the volatility of dynamic grid tariffs, for example by limiting tariff fluctuations or implementing more stable tariff structures. However, doing so may also weaken the price signal intended to shift demand and reduce congestion. This highlights a central trade-off: stronger and more dynamic price signals can improve congestion-related incentives, but may simultaneously increase price volatility and bill uncertainty for grid users.

These effects are not limited to consumers. The introduction of dynamic grid tariffs also affects market parties whose roles, responsibilities, and interactions influence whether the mechanism can be implemented and coordinated effectively. Therefore, the following section discusses the relevant market roles and their functions within the electricity system.

2.3.9 Actor roles and market coordination

The Dutch electricity system consists of core system actors and several market roles and functions (Tennet, n.d.). The core system actors are the Transmission System Operator (TSO) and Distribution System Operators (DSOs), which are responsible for ensuring the functionality, accessibility, and reliability of the electricity grid (Ruester, Schwenen, Batlle, & Pérez-Arriaga, 2014). In this research, Stedin represents the DSO. As a grid operator, the DSO is responsible for managing and maintaining the distribution network, ensuring sufficient transport capacity, and managing grid congestion. Its responsibilities and authority are defined in the Dutch Energy Act and must be exercised in accordance with principles such as transparency and non-discrimination, under the supervision of the Authority for Consumers and Markets (ACM) (Rijksoverheid, 2026). Grid tariffs constitute an important instrument through which network costs are recovered and network use can potentially be influenced.

In addition to these system actors, several market roles contribute to the functioning of the electricity system. Consumers are end-users of electricity and pay both energy prices and grid tariffs. Their electricity consumption and generation increasingly influence local grid conditions, particularly with the growing adoption of technologies such as photovoltaic panels, electric vehicles, heat pumps, and batteries. Consumers differ considerably in their ability to respond to price signals because of differences in flexibility, financial resources, knowledge, and access to flexible technologies (Winther & Sundet, 2023). This heterogeneity is particularly relevant for dynamic grid tariffs, since consumers with greater flexibility have more opportunities to adapt their consumption to tariff signals.

The ability of consumers to respond to dynamic price signals can be enhanced through automation. Fotouhi Ghazvini et al. (2019) describe Home Energy Management Systems (HEMS) as software platforms that enable the monitoring, management, and optimisation of residential energy consumption. Wang et al. (2023) also point out the importance of such systems, naming the widespread adoption of smart meters as a prerequisite for implementing dynamic grid tariffs. By coordinating flexible assets and incorporating external signals such as electricity prices and grid tariffs, a HEMS can automatically shift consumption or generation in response to changing system conditions. Consequently, automation can reduce the need for active consumer participation and increase the practical responsiveness of flexible residential loads (Fotouhi Ghazvini et al., 2019).

Companies can fulfil several market roles. Suppliers provide electricity to consumers and, under the Dutch *leveranciersmodel*, are also responsible for billing consumers for grid tariffs on behalf of the DSO (ACM, 2013). Balance Responsible Parties (BRPs) are responsible for maintaining the balance between supply and demand within their portfolios, whereas Balancing Service Providers (BSPs) provide flexible capacity that can be activated to support system balancing (Tennet, n.d.). Congestion Service Providers (CSPs) provide flexibility for congestion management, for example through GOPACS or bilateral arrangements (Tennet, n.d.). Aggregators can coordinate flexible assets across multiple consumers, allowing distributed flexibility to participate collectively in electricity and flexibility markets (Tennet, n.d.).

It is important to distinguish between organisations and market roles. The roles described in this section are functional roles within the electricity system and are not necessarily performed by separate organisations. A single company may fulfil multiple roles simultaneously, for example acting as both supplier and Balance Responsible Party (BRP), or as both Congestion Service Provider (CSP) and aggregator. Likewise, companies can also be grid users themselves and therefore occupy the role of consumer in addition to other market roles. The actor analysis therefore distinguishes between roles rather than assuming a one-to-one relationship between organisations and market functions.

To regulate the interactions between these actor roles, formal relationships have been defined in a regulatory framework called the Energiewet (2026).

The Energiewet

First, the position of the DSO (Stedin) is defined within the Dutch Energy Act (Rijksoverheid, 2026). As a regulated entity, Stedin is responsible for managing, maintaining, and operating the electricity grid. Its authority includes controlling grid access and transport capacity, as well as managing congestion. Specifically, the DSO is permitted to refuse new connections in cases of insufficient capacity (Art.

3.38) and to procure congestion management services from market parties such as Congestion Service Providers (CSPs) (Art. 3.29). At the same time, Stedin operates under strict regulatory oversight by the Authority for Consumers and Markets (ACM), which monitors its activities and has the authority to intervene (Art. 3.4). Furthermore, the DSO must comply with key regulatory principles, including non-discrimination, transparency, and fairness. As a result, while Stedin possesses significant operational control over the grid, its actions are constrained by regulatory requirements and external supervision.
Second, suppliers play a central role in the interaction between the grid operator and end users. Both grid users and the DSO depend on suppliers for the delivery of electricity and the implementation of dynamic grid tariffs. This dependency is rooted in the Dutch *leveranciersmodel* (supplier model), in which suppliers are responsible for billing consumers, including the incorporation of grid tariffs into energy bills (ACM, 2013). Consequently, any changes in tariff structures, such as the introduction of dynamic grid tariffs, must be implemented through supplier systems. This positions suppliers as a critical intermediary in the system, linking regulatory design and technical implementation to consumer-facing outcomes.

These roles are strongly interconnected. Changes in consumer behaviour resulting from dynamic grid tariffs can affect supplier billing processes, BRP portfolio positions, the availability of flexibility for CSPs and aggregators, and ultimately the loading of the distribution network. Dynamic grid tariffs should therefore not be considered solely as a DSO–consumer interaction, but as a mechanism embedded within the broader electricity market. The responsibilities and interactions described in this section provide the basis for the actor analysis in Chapter 4.

Rapidly changing market

While issues like volatility and grid congestion have been identified, the electricity market is undergoing rapid structural changes, with new actors such as aggregators emerging and taking on increasingly important roles (García, Troncia, & Ávila, 2025). These developments are fundamentally altering the dynamics between actors within the system. As electricity systems operate as interconnected multi-actor environments, effective functioning depends on the interaction and coordination between all involved parties. Therefore, Garciá et al. (2025) highlight that the fast-changing dynamics between market roles require ongoing analysis, to prevent outdated assumptions resulting in wrongful outcomes. This makes it essential to consider not only individual actor objectives, but also how these objectives interact at the system level. This valuation is confirmed by the International Energy Agency (IEA), who stress that complementary mechanisms eventually should become structural and "must align with market signals through co-ordinated reform" (IEA, 2025).

2.4 Research gap and implications for this research

The literature shows that dynamic grid tariffs can contribute to congestion management by providing price signals that reflect grid conditions. At the same time, these mechanisms may increase price volatility, uncertainty, and complexity for grid users and market actors. Existing studies propose several tariff designs and mitigation instruments, such as capacity-based mechanisms, price caps, reliability options, aggregation, and hybrid market structures. However, these studies often focus on specific tariff mechanisms, specific actor groups, or specific evaluation objectives, rather than on the integrated design of a mechanism that balances congestion reduction, volatility mitigation, and actor-specific feasibility.

First, existing tariff evaluation frameworks provide a useful basis for assessing dynamic tariffs, particularly through criteria such as cost recovery, cost reflectiveness, non-discrimination, cost efficiency, and simplicity. However, the electricity system is changing due to the emergence of flexibility service providers, aggregators, and stronger interactions between tariff signals, consumer behaviour, and balancing responsibilities. As a result, existing criteria may not fully capture the current objectives, constraints, and responsibilities of all relevant actors. This creates a need to reassess and update the translation of actor interests into evaluation criteria.

Second, the literature lacks a mechanism design that is explicitly based on current actor objectives and that systematically balances the trade-offs between these objectives. Existing approaches often focus

on a limited number of objectives, such as economic efficiency, cost reflectivity, or consumer protection. However, they do not fully integrate the broader set of actor-specific goals and constraints that arise in a changing multi-actor electricity system. Therefore, there is a need for a design-oriented study that first identifies current actor objectives, translates them into design criteria, and uses these criteria to design and evaluate alternative grid-tariff mechanisms.

The following chapters address this gap by performing an actor analysis, deriving a criteria set, developing alternative grid-tariff mechanisms, and evaluating their performance under dynamic grid tariffs.

3 Methodology

To answer the research questions defined in the introduction, several methods are applied in this research:

3.1 Subquestion 1

Which actors are impacted by dynamic grid tariffs, and what are their main objectives, stakes, constraints, and instruments?

This is the first step of the DSR method. In this step, the relevant actors are identified together with their objectives, constraints, instruments, and interests. This provides an understanding of which actors should be included in the analysis and which actor-specific factors shape the problem situation. These insights form the basis for the subsequent formulation of design goals and evaluation criteria. This step consists of two methods:

A) Actor analysis

First, the actor analysis methodology developed by Bert Enserink is applied. This method is specifically designed to analyse complex multi-actor settings, making it well suited for examining the actor field in this research (Enserink et al., 2022). This analysis consists of five steps:

- Problem formulation
- Setting up an inventory of actors involved
- Mapping formal relations
- Setting up an inventory of interests, constraints, and requirements.
- Deriving interdependencies: resources, conflicts and alignments

The actor analysis methodology developed by Enserink et al. (2022) is selected because dynamic grid tariffs are embedded in a multi-actor electricity system in which the feasibility of a mechanism depends not only on technical performance, but also on actor objectives, resources, constraints, and interdependencies. The method provides a structured way to identify these elements and is therefore more suitable than analysing actors individually without explicitly considering their mutual dependencies.
These five steps provide a structured approach for identifying the relevant actors and analysing their respective stakes in the problem situation. By building on existing knowledge, they provide a clear overview of the actor landscape and the relationships, interests, and dependencies that shape it.

To verify and complement the literature-based actor analysis, semi-structured interviews are conducted with relevant market actors. This is particularly important because the electricity market is rapidly changing and current operational concerns, objectives, constraints, instruments, and interests may not yet be fully reflected in academic literature. The interviews are therefore used to validate the literature-based findings and to identify additional actor-specific concerns and requirements. Two categories of participants are included: market organisations and consumers. Because these groups occupy different positions within the electricity system, separate interview guides are used for each category, as explained in the following section.

B) Interviews

To complement the literature-based actor analysis, semi-structured interviews were conducted with relevant actors in the Dutch electricity system. The interviews were used to obtain empirical insights into actor interests, concerns, constraints, and requirements regarding the introduction of dynamic grid tariffs. A semi-structured approach was chosen to ensure that comparable topics were addressed across interviews, while allowing the discussion to follow issues that were particularly relevant to the

role and expertise of each participant.

Interview participants were selected to represent the market roles identified in Chapter 2 based on (IEA, 2025; Tennet, n.d.). The aim was to include different perspectives on the implementation of dynamic grid tariffs and thereby obtain a broad understanding of stakeholder interests, market constraints, and practical implementation considerations. Representatives of organisations covering these roles were subsequently approached. Initial contacts were obtained through Stedin's professional network, as this research was conducted in collaboration with Stedin. Where this did not provide sufficient representation of the identified market roles, additional organisations were approached. An overview of the organisations approached and their corresponding market roles is provided in Table 2.

Table 2: Overview of selected companies and their market roles

Company	**Market role(s)**
Frank Energie	Supplier (flexibility-oriented)
Energie VanOns	Supplier
Pure Energie	Supplier, BRP
Distro Energy	Supplier
Engie	Supplier, BRP
Energie Nederland	Industry association / stakeholder organisation
Eneco	Supplier, BRP
PVNED	BRP
Groendus	CSP (Congestion Service Provider), Aggregator
Next Kraftwerke	CSP, BRP, Aggregator
Stedin	DSO (Distribution System Operator, regulated)
EddyGrid	Aggregator

Of the organisations listed in Table 2, PVNED and Next Kraftwerke were not interested in participating. The remaining organisations participated in the study, resulting in interviews with representatives of ten market organisations.

The final set of participants covered all market roles identified as relevant in the literature review. The interviews therefore provided empirical perspectives that could be compared with the literature and used to complement the literature-based actor analysis.

The interviews with market parties lasted approximately one hour. A common interview guide was used, while individual questions were adapted to the role and expertise of the participant. The following questions formed the core of the interviews:

- What is the primary role of the organisation in the electricity market?
- What is your perspective on the potential of dynamic grid tariffs?
- What are your main concerns regarding dynamic grid tariffs?
- Which characteristics of dynamic grid tariffs create these concerns?
- Which characteristics should a future grid tariff mechanism have?
- To what extent could dynamic grid tariffs create opportunities for your organisation?

Questions focused on the actor's role and interests within the electricity system, their perspective on dynamic grid tariffs, and the opportunities, concerns, and requirements associated with their implementation. Where necessary, the questions were adapted to reflect the specific responsibilities and expertise of each participant. Using these questions as a guide, the interviews addressed several recurring themes: the perceived potential of dynamic grid tariffs, the main concerns associated with their introduction, possible opportunities, and the underlying characteristics of the tariff mechanism that give rise to these concerns or opportunities. Together, these questions provided insight into the interests, constraints, and requirements of the different actors, as well as how specific elements of grid tariff mechanisms may affect them. The interview findings are subsequently used to support the actor analysis, the formulation of evaluation criteria, and the development of conceptual grid-tariff

mechanisms by identifying which design choices may create favourable or unfavourable effects for particular actors.

In addition to the market-party interviews, 4 consumers participating in Stedin's EmPower pilot in the Vruchtenbuurt were interviewed. Their direct experience with a dynamic grid tariff provides insights into the practical implications of the mechanism from a consumer perspective. However, these participants voluntarily enrolled in the pilot and may therefore be more interested in energy flexibility and more willing to adapt their consumption than the average consumer. Their experiences should consequently not be interpreted as representative of all electricity consumers. This limitation is particularly relevant given the consumer heterogeneity discussed in Section 2.3.8.

These consumer interviews lasted approximately 20 minutes and focused on participants' experiences with the EmPower pilot. Based on the literature discussed in Section 2.3.8, particular attention was given to costs, complexity, required actions, information provision, and the ability to respond to tariff signals. The following questions were used as a guide:

- What is your overall experience with the EmPower mechanism?
- What were your main reasons for participating in the pilot?
- Did you experience any barriers that limited your ability to respond to tariff signals?
- How much effort does responding to tariff signals require?
- What information do you need to respond, and how far in advance should this information be available?

The questions focused on participants' practical experience with the EmPower mechanism, particularly which aspects worked well, which created difficulties, and what improvements they considered necessary. The interviews therefore provided insight into how consumers perceive tariff complexity, price signals, flexibility options, and potential risks. These findings are used to identify consumer-related requirements and concerns and to support the formulation of evaluation criteria and the design of conceptual tariff mechanisms.

Following each interview, the responses were structured according to the recurring themes in the interview guide, including actor interests, concerns, opportunities, requirements, and relevant tariff characteristics. These findings were subsequently compared across actors and with the literature-based actor analysis. Recurring or contrasting perspectives were used to refine the actor interests and design goals. The resulting empirical insights are presented in the actor analysis.

3.2 Subquestion 2

Which evaluation criteria can be derived from the literature and actor objectives and constraints to guide the design and evaluation of grid-tariff mechanisms?

The literature review provides the theoretical basis for the evaluation framework by identifying existing dimensions and criteria used in previous electricity tariff studies. These literature-based criteria form the initial framework for this research. The findings from the actor analysis are subsequently used to assess whether this framework sufficiently represents the objectives, constraints, and concerns of the actors affected by dynamic grid tariffs.

This combined approach is selected because neither source is sufficient on its own. Relying solely on existing literature may overlook actor-specific concerns and recent developments in the electricity market, whereas deriving criteria only from the actor analysis would make the evaluation framework strongly dependent on the perspectives of the selected participants and the specific research context. Combining both sources therefore provides an evaluation framework that is both theoretically grounded and responsive to the current market context.

For each identified actor requirement, it is assessed whether it is adequately represented by an existing literature-based criterion. Where this is the case, the existing criterion is retained or refined for the

context of this research. Where an actor requirement is not sufficiently represented, an additional criterion is introduced. In this way, the literature provides the theoretical foundation of the evaluation framework, while the actor analysis and interview findings ensure that the criteria reflect actor-specific concerns in the current Dutch electricity-market context.

After the criteria have been identified, they are operationalised to enable a consistent comparison of the alternative mechanism designs. First, the criteria are classified according to their evaluation level as system-level, actor-level, or both. This distinction clarifies whether a criterion primarily describes overall mechanism performance or consequences for specific actors. Second, the appropriate evaluation method is determined by distinguishing between quantitative and qualitative criteria. Finally, each criterion is translated into either a measurable numerical indicator or a predefined qualitative assessment method. This operationalisation translates the initially abstract criteria into observable and comparable measures that can be applied consistently across the alternative mechanisms. The detailed derivation, selection, and operationalisation of the criteria are presented in Chapter 5.

3.3 Subquestion 3

What grid-tariff mechanisms can be designed to incentivize congestion-reducing behaviour through dynamic grid tariffs while mitigating the risks for grid users identified through the literature and actor analyses?

This subquestion focuses on the design of alternative grid-tariff mechanisms. To ensure a structured and systematic exploration of potential solutions, the design process is divided into three consecutive steps: (1) defining the design space, (2) exploring alternative designs, and (3) selecting representative configurations for evaluation.

A design-space approach is used because the tariff mechanism cannot be represented by a single design choice, but consists of several interacting dimensions. Exploring these dimensions explicitly makes it possible to develop alternatives systematically rather than relying on ad hoc mechanism proposals. It also creates traceability between individual design choices and their expected effects on the objectives and constraints identified in the preceding actor analysis. This approach is therefore particularly suitable for this research, as the purpose is not to identify one predetermined tariff mechanism, but to explore how different combinations of design choices influence the trade-offs between performance criteria.

Step 1: Defining the design space
The first step consists of defining the design space through the identification of key design variables. These variables represent the main dimensions along which tariff mechanisms can vary, such as tariff structure, targeted demand, risk allocation, and time horizon. Rather than approaching the design process in a one-dimensional manner, the use of design variables enables a structured and transparent exploration of alternative configurations.

For each design variable, multiple discrete options are defined based on insights from literature, the actor analysis, and stakeholder interviews. These options represent technically and institutionally plausible configurations informed by existing tariff structures, literature, and stakeholder insights. By explicitly defining both variables and their possible values, the design process becomes reproducible and allows for a clear link between design choices and resulting outcomes.
The combination of design variables and their respective options constitutes the design space. Within this space, both extreme and intermediate configurations can be constructed, enabling the analysis to capture the key trade-offs between system objectives such as price signal strength, consumer exposure, predictability, and implementation complexity. Importantly, the objective is not to evaluate all possible combinations, but to structure the solution space and identify relevant design directions.

Step 2: Exploration of design alternatives

In the second step, the defined design space is explored using morphological analysis (Ritchey, 1998). This method is widely applied in engineering and design research to structure complex problems involving multiple interacting variables. It allows for the systematic construction of alternative configurations by combining different values of the identified design variables. Therefore, this method is selected to structure the exploration of the design space systematically and reduce the risk that relevant design directions are overlooked due to an ad hoc or researcher-driven selection process.

The exploration starts with the development of extreme configurations, in which individual design variables are maximised or minimised in line with specific design objectives. These extreme cases define the boundaries of the design space and serve as analytical benchmarks, making fundamental trade-offs between competing objectives, such as volatility and stability, more explicit. Starting from these extremes creates a clear progression from designs that prioritise a single aspect of performance towards designs that seek to balance multiple objectives. Without these benchmark cases, the nature and severity of the underlying trade-offs would be less apparent.

Building on these extreme configurations, intermediate designs are developed by combining elements from different parts of the design space. The purpose of this step is to identify plausible grid-tariff mechanisms that achieve a better balance between competing objectives. For example, a mechanism that maximises responsiveness to grid conditions may also result in excessive tariff or cost volatility, whereas a highly stable mechanism may provide weaker incentives for congestion-reducing behaviour. By combining design elements from both ends of the spectrum, intermediate configurations can be developed that retain the advantages of each approach while limiting their disadvantages.

This structured exploration ensures that multiple design directions are considered, reducing the risk of biased selection and enabling a comprehensive analysis of the solution space. Conceptually, this process can be summarised as:

$$\text{Design variables} \rightarrow \text{Design space} \rightarrow \text{Design alternatives}$$

Step 3: Selection of designs for evaluation

The final step consists of selecting a limited number of representative designs from the explored set of alternatives. Rather than selecting extreme configurations, the focus lies on mechanisms that provide a balanced performance across the previously defined criteria. The selected designs represent different positions within the design space and capture the most relevant trade-offs between the performance criteria. By selecting a manageable subset of configurations, the following evaluation phase remains analytically tractable while still covering the most important solution directions.

These selected mechanisms form the basis for the evaluation in Subquestion 4, where their performance is assessed both qualitatively and quantitatively.

3.4 Subquestion 4

How do alternative grid-tariff mechanisms perform for different household profiles and electricity market actors, based on the evaluation criteria defined in Step 2?

The alternative grid-tariff mechanisms are evaluated against the criteria derived in Subquestion 2. This evaluation is required to determine how the different design choices affect the objectives and requirements identified earlier in the research and to make the trade-offs between alternative mechanisms explicit. Because the criteria represent different dimensions of performance, no single indicator is sufficient to assess the mechanisms. A combination of quantitative and qualitative evaluation is therefore applied.

Quantitative evaluation refers to the systematic calculation and comparison of predefined numerical indicators across the selected mechanism designs. The simulation model is used to generate the numerical outputs required for these indicators, such as tariff levels, consumer costs, tariff revenues, flexibility benefits, and signal interactions. These outputs are subsequently translated into the quantitative indicators operationalised in Chapter 5 and compared across mechanisms and, where relevant, across

household profiles.

Qualitative criteria are evaluated using the predefined assessment rules developed in Chapter 5. These criteria concern characteristics such as implementation complexity, additional burdens, clarity of the mechanism, non-discrimination, and actor-role delineation, which cannot be represented meaningfully by the simulation model alone.

Evaluation model
A simulation model is developed to generate the numerical outputs required for the quantitative evaluation. Modelling is used because the proposed mechanisms have not yet been implemented in practice in this context, and empirical performance data are therefore unavailable. A simulation approach makes it possible to apply each mechanism under identical network conditions, consumer profiles, and simulation periods, enabling a controlled comparison between the designs.

A market-based simulation model is selected because the research focuses on how alternative tariff structures and grid-tariff mechanisms translate network conditions into price signals and how these signals affect consumer costs, flexibility incentives, and other economic outcomes. A detailed power-flow model is therefore not required for the main objective of the evaluation. Instead, network loading and congestion conditions are used as exogenous inputs to the tariff mechanisms. The resulting model outputs provide the numerical basis for calculating the quantitative indicators defined in Chapter 5.

A detailed description of the model structure, household archetypes, input data, and optimisation methods is provided in Chapter 7.

Evaluation table

In the second step, the quantitative and qualitative findings are combined in an evaluation table. This method is used to provide a transparent and consistent comparison across mechanisms while retaining the different dimensions represented by the evaluation criteria. Rather than aggregating all criteria into a single score, the table is used to identify strengths, weaknesses, and trade-offs between the alternative designs. This supports an assessment of which design choices provide favourable balances between competing objectives and where important compromises remain.

Together, the answers to the four subquestions provide the basis for answering the main research question.

3.5 Data sources

To apply the methods described in the previous section, multiple data sources were required. In the first step, data was collected directly from grid users. In the earlier stages of this project, Stedin has already collected some data on user profiles, which has been provided to this research. This data provided insights into consumer behaviour, demand flexibility, and vulnerability to price volatility.
Altogether, data was collected through four complementary sources. First, a literature review provided the conceptual foundation of the research and shape the scope of the topic. Second, semi-structured interviews were conducted to capture the objectives, constraints, and needs of key actors. Third, Stedin provided data on grid user profiles and the loading profile of the chosen MSR in Den Haag. Last, standardised yearly consumer demand profiles were extracted from the website of Energie Data.

The congestion conditions were provided through network datasets that specify where and when congestion occurs within the distribution grid. For example, the data indicate whether a household connected to a specific MSR experiences congestion during particular time periods. The dataset includes (1) the geographical location of congestion (such as transmission lines or substation zones), (2) the time resolution and duration of congestion events, and (3) an intensity indicator such as loading levels and/or congestion classifications. These congestion indicators were used to construct tariff scenarios within the simulation model. As the model does not perform physical power-flow calculations, the data was purely used as inputs for tariff generation and the assessment of economic effects.

4 Actor analysis

4.1 Actor analysis

The literature review identified the main actors and market roles that are directly or indirectly affected by the introduction of dynamic grid tariffs. Building on these formal roles, this section analyses their position within the proposed tariff system in terms of three dimensions: *stakes*, *constraints*, and *instruments*. Stakes describe the outcomes that an actor seeks to achieve or protect, constraints represent factors that limit the actor's ability to respond to the tariff mechanism, and instruments describe the means available to influence the functioning or outcomes of the system.
The analysis focuses on six actor roles that are considered most relevant to the design of dynamic distribution grid tariffs: the DSO (Stedin), consumers, suppliers, CSPs, aggregators, and BRPs. BSPs are not analysed separately because their role is primarily related to system balancing rather than distribution-level congestion management. Nevertheless, interactions between grid tariff signals and other electricity-market signals remain relevant through their potential impact on BRPs. The TSO is also excluded because the scope of this research is limited to distribution-level congestion. Interactions with transmission-level balancing are nevertheless considered indirectly through the BRP perspective.

4.2 Problem formulation

Dynamic grid tariffs affect grid conditions, therefore affecting parties involved with the electricity market. Consumers are faced with varying costs, aimed at changing their demand patterns to reduce grid congestion. Stedin, the DSO, plans to implement dynamic grid tariffs to reduce grid congestion. This new type of grid tariffs is meant to become a sustainable part of the energy system, which requires cooperation and adoption of market parties. Next to Stedin and Consumers, more parties are directly involved with the grid tariff system. The goal of this analysis is to identify and map the stakes and constraints of the actors involved in order to make an overview of the market context.

4.2.1 Actor stakes, constraints, and instruments

Based on the actor roles identified in the literature review, the introduction of dynamic grid tariffs affects actors in different ways. Their position within the proposed tariff system is analysed in terms of three dimensions: stakes, constraints, and instruments. Stakes describe the outcomes that an actor seeks to achieve or protect, constraints represent factors that limit the actor's ability to respond to the tariff mechanism, and instruments describe the means available to influence the functioning or outcomes of the system.

For the Distribution System Operator (DSO), represented by Stedin in this research, the primary stake is maintaining a reliable distribution network while reducing congestion. In the context of dynamic grid tariffs, this means that tariff signals should incentivise consumers to reduce import or export during periods in which network capacity is scarce. At the same time, the tariff mechanism should provide sufficient cost recovery and should be accepted and implemented by market participants, since its effectiveness ultimately depends on their ability and willingness to respond. The DSO is constrained by its regulated position and cannot freely introduce new tariff structures. Furthermore, it cannot directly control residential consumption and therefore depends on consumers and market parties to respond to the tariff signal. Its main instruments are tariff design and network information. By translating local network conditions into differentiated tariff signals, the DSO can provide an economic incentive to shift consumption or generation away from congested periods.

Consumers are assumed to primarily seek affordable and reliable access to electricity while maintaining their desired level of comfort. Under dynamic grid tariffs, their electricity costs become increasingly dependent on when electricity is consumed or generated. Consumers therefore have an incentive to adapt their behaviour when the potential financial benefit outweighs the inconvenience associated with doing so. However, their ability to respond differs substantially. A household without flexible technologies has considerably fewer opportunities to change its load profile than a household equipped with an electric vehicle, heat pump, battery, or controllable PV system. Flexibility may additionally be constrained by comfort requirements, knowledge, available time, and financial resources. This creates a potential distributional issue, as consumers with greater technological flexibility may be better able to

avoid high tariffs than consumers with limited flexibility. Consumers can respond by shifting, reducing, or, where applicable, increasing electricity consumption or generation. The availability of flexible technologies increases these possibilities, while a HEMS can automate the response and reduce the need for active consumer decision-making.

Energy suppliers have an interest in maintaining efficient billing processes, limiting implementation costs, and preserving stable business operations. Dynamic grid tariffs introduce additional complexity because time-varying tariff values must be incorporated into consumer billing. Suppliers have limited influence over the design of the grid tariff itself, while nevertheless being responsible for processing tariff information through the *leveranciersmodel*. Highly granular or frequently changing tariffs may therefore increase requirements for data processing, billing, communication, and IT infrastructure. The main instruments available to suppliers relate to the implementation and communication of the tariff. Their billing systems provide the interface through which tariff costs are ultimately transferred to consumers. Furthermore, suppliers may combine grid tariff information with electricity price signals in their products and services, making the interaction between both price signals relevant.

Congestion Service Providers (CSPs) have an interest in maintaining the economic value of congestion-management services. Dynamic grid tariffs can create additional incentives for flexible behaviour, but these incentives may interact with existing flexibility markets and services. Their business case therefore depends on whether sufficient economic value can be obtained from coordinating or providing flexible capacity. Their ability to exploit this flexibility is constrained by the availability of controllable assets and by the quality, timing, and predictability of tariff and congestion information. Uncertain or rapidly changing signals can make optimisation more difficult. CSPs and aggregators can respond by coordinating flexible consumption, generation, and storage across consumers. This allows distributed flexibility to respond collectively to congestion signals and can reduce the need for individual consumers to actively optimise their behaviour.

Balance Responsible Parties (BRPs) seek to maintain balance within their portfolios and minimise exposure to imbalance costs. Dynamic grid tariffs introduce an additional price signal that can alter consumer demand independently of wholesale-market and balancing incentives. BRPs therefore have an interest in tariff signals that do not unnecessarily conflict with existing market signals and that result in sufficiently predictable consumer responses. At the same time, BRPs do not control the grid tariff and may have limited ability to anticipate behavioural responses to highly dynamic signals. If large groups of consumers respond simultaneously to local congestion signals, portfolio demand may deviate from previously expected demand, potentially increasing imbalance exposure. BRPs can mitigate these risks through portfolio management, forecasting, and adjustments to their market positions. Their ability to do so improves when tariff information is available sufficiently far in advance and when consumer responses are reasonably predictable.

Finally, aggregators have an interest in efficiently coordinating flexibility across a portfolio of consumers or prosumers and maintaining a viable long-term business case for providing these services. In the context of residential flexibility, this requires the coordination of a large number of relatively small flexible assets, such as electric vehicles, heat pumps, batteries, and PV systems. Aggregators therefore depend strongly on accurate and timely tariff and congestion information to optimise their portfolio and anticipate changes in consumer demand. Their ability to provide these services is constrained by the availability of controllable assets, reliable communication infrastructure, and clear agreements regarding access to and control of household flexibility. Ambiguity regarding responsibilities for data exchange, asset control, system monitoring, and communication can further complicate the implementation of aggregation services. The main instrument available to aggregators is the coordinated optimisation of flexible assets across participating households. Through automated control, for example via Home Energy Management Systems (HEMS), aggregators can translate tariff or congestion signals into coordinated changes in consumption, generation, or storage without requiring continuous active response from individual consumers. This makes clear role allocation, reliable information exchange, and automation important conditions for aggregators to provide scalable flexibility services.

4.2.2 Synthesis of actor interests and preliminary requirements

The actor analysis reveals that the introduction of dynamic grid tariffs creates both aligned and conflicting interests, which translate into several preliminary requirements for tariff design. These

requirements follow from the interaction between actor objectives and their operational constraints and provide the first step towards the formulation of the design criteria.

Trade-offs

A first trade-off exists between the effectiveness of the congestion signal and the predictability and simplicity of the tariff mechanism. The DSO benefits from tariff signals that closely reflect local network conditions and provide strong incentives for congestion reduction. Consumers and suppliers, in contrast, generally benefit from tariff structures that are understandable and predictable. Highly dynamic signals may improve the temporal reflectiveness of grid tariffs, but can simultaneously increase uncertainty and implementation complexity for market participants. The tariff mechanism should therefore provide an effective congestion signal while limiting unnecessary complexity and volatility.
A second trade-off concerns differences in the ability of consumers to respond to tariff signals. Consumers with flexible technologies have greater opportunities to shift their consumption and potentially reduce their costs, whereas consumers with limited flexibility have fewer possibilities to adapt. Strong flexibility incentives may therefore result in unequal cost exposure across consumer groups. Consequently, the tariff mechanism should limit disproportionate cost exposure and account for differences in consumer flexibility, while still providing sufficient economic incentives for flexible behaviour.
A third consideration concerns the interaction between dynamic grid tariffs and other market signals. Consumers may simultaneously respond to electricity prices, grid tariffs, balancing incentives, and revenues from flexibility services. A grid tariff that provides an effective congestion-management signal could therefore conflict with incentives originating elsewhere in the electricity system. This is particularly relevant for BRPs, CSPs, suppliers, and aggregators, whose activities depend on sufficiently predictable signals and reliable information. Dynamic grid tariffs should therefore provide timely and reliable tariff information and should avoid unnecessary conflicts with existing electricity-market and balancing signals.

Finally, implementation of the tariff mechanism depends on the operational and regulatory constraints of the actors involved. Suppliers are responsible for incorporating grid tariffs into consumer billing and therefore benefit from mechanisms that can be integrated into existing processes without disproportionate implementation burdens. The DSO operates within a regulated environment, meaning that the mechanism must be technically feasible and compatible with the applicable regulatory framework. Aggregators and CSPs require a clear long-term business case, which indicates the need for stable market conditions. Practical implementability and regulatory compatibility therefore constitute additional requirements for tariff design.

Together, these preliminary requirements demonstrate that dynamic grid tariffs cannot be evaluated solely based on their ability to reduce congestion. Their effects on consumers, market participants, flexibility incentives, implementation, and interactions with other market signals must also be considered.

Beyond these trade-offs and requirements, the actor analysis also identifies a potentially important role for aggregators.

Aggregator potential

By coordinating flexibility across a larger portfolio of consumers, aggregators can benefit from scale and partly offset individual deviations within the portfolio. At the same time, aggregation can reduce the complexity faced by individual consumers. Rather than requiring households to continuously interpret and respond to changing grid tariffs, an aggregator can optimise flexible assets on their behalf through automated control. This creates the possibility for aggregators to translate a relatively complex tariff mechanism into a simpler service for consumers. The value created through coordinated flexibility may, in turn, support a viable business case for providing such optimisation services.

In the following section, these preliminary requirements are further refined and validated using insights obtained from the stakeholder interviews.
Table 3 shows a short overview of the involved actors and their market functions.

Table 3: Overview of core actors and their roles in the electricity system

Actor	Role / Position in the system
DSO (Stedin)	The distribution system operator responsible for managing, maintaining, and expanding the electricity grid. Designs and implements (dynamic) grid tariffs to reduce congestion while ensuring reliability and efficiency.
Consumers (Grid users)	End-users of electricity who pay grid tariffs. Their consumption behaviour is influenced by price signals and plays a key role in determining the effectiveness of congestion management.
Suppliers	Responsible for delivering electricity to consumers and handling billing under the supplier model. They pass on grid tariffs to consumers and develop contract structures that shape consumer incentives.
BRPs	Responsible for balancing electricity supply and demand within their portfolio. They are exposed to imbalance risks when consumption patterns change due to dynamic tariffs.
CSPs	Provide flexibility by adjusting consumption or generation (e.g., via EVs, batteries, or industry) to alleviate grid congestion. They monetize flexibility by responding to congestion signals.
Aggregators	Aggregate and coordinate flexibility from multiple consumers or prosumers and commercially offer this flexibility to market parties and system operators.

4.3 Interview insights: empirical actor analysis

The interviews complement the literature-based actor analysis with empirical insights into the interests, concerns, and requirements of actors directly involved in the Dutch electricity system. They provide additional understanding of how dynamic grid tariffs are perceived in practice and identify operational, behavioural, and implementation considerations that may not be fully captured by the literature.
A recurring observation from the interviews is that perspectives differ not only between market roles, but also between actors performing similar roles. This is particularly visible among electricity suppliers. Traditional commodity-oriented suppliers generally expressed concerns about the additional complexity associated with dynamic grid tariffs, including operational costs and increased customer support requirements. Flexibility-oriented suppliers, in contrast, were generally more positive about dynamic tariffs, as these create opportunities to offer flexibility services and optimise electricity consumption on behalf of consumers.
For BRPs, CSPs, and Aggregators, accurate and timely information emerged as an important requirement. BRPs require reliable information to forecast their portfolios and limit imbalance exposure, while CSPs require information on expected grid conditions to effectively anticipate and deploy flexibility. These and other actor-specific findings are discussed in the following sections.

4.3.1 Interview process

Interview participants were selected to represent the market roles identified in Chapter 2 based on (IEA, 2025; Tennet, n.d.). The aim was to include different perspectives on the implementation of dynamic grid tariffs and thereby obtain a broad understanding of stakeholder interests, market constraints, and practical implementation considerations. An overview of the organisations approached and their corresponding market roles is provided in Table 2.

Table 4: Overview of selected companies and their market roles

Company	Market role(s)
Frank Energie	Supplier (flexibility-oriented)
Energie VanOns	Supplier
Pure Energie	Supplier, BRP
Distro Energy	Supplier
Engie	Supplier, BRP
Energie Nederland	Industry association / stakeholder organisation
Eneco	Supplier, BRP
PVNED	BRP
Groendus	CSP (Congestion Service Provider), Aggregator
Next Kraftwerke	CSP, BRP, Aggregator
Stedin	DSO (Distribution System Operator, regulated)
EddyGrid	Aggregator

In addition to these market parties, four households were interviewed. While the market parties shown in table 4 are effected as a company, consumers are the target actor of these dynamic grid tariffs. They are confronted with the price signal, which is why they have to be included in the design of grid-tariff mechanisms that are intended to balance the stakes of involved actors. A more elaborate description of the interview process is provided in Chapter 3.

The interview findings were organised according to the relevant actor roles and used to complement the actor interests identified in the literature. Where the interviews revealed concerns or requirements that were not sufficiently captured by the literature-based analysis, these were included as additional considerations. Summarised transcripts of the interviews can be found in Appendixes B and C. The resulting actor perspectives are discussed in the following sections and subsequently translated into design goals that guide the design process.

4.3.2 Supplier perspective

Suppliers expressed strong concerns regarding implementation complexity and operational burden. As they are responsible for billing under the *leveranciersmodel*, increased tariff complexity directly affects their systems and processes. Dynamic tariffs are perceived as difficult to integrate, requiring significant IT investments and increasing customer communication demands. In addition, suppliers highlighted risks related to price volatility and customer acceptance. Increased bill uncertainty may lead to customer dissatisfaction, higher churn, and reputational risks. These concerns reinforce the need for predictable and transparent tariff structures. Last, suppliers expressed concerns about CSPs and other flexibility-steering parties affecting demand within their portfolio.

4.3.3 Consumer perspective

Interviews indicate that consumers have limited willingness and ability to actively respond to dynamic price signals. Rather than purely optimizing for cost, consumers prioritise simplicity, comfort, and predictability. An important driver of acceptance is the extent to which consumers understand and recognise the purpose of the tariff system. Furthermore, consumers are highly heterogeneous in terms of flexibility. While some households possess flexible assets such as EVs or heat pumps, others have little to no flexibility, resulting in unequal impacts under uniform tariff exposure. Automation is therefore considered essential, as manual demand response is largely unrealistic for most users. However, automation does not remove all practical limitations. For many household devices, frequent switching on and off is undesirable, as it may reduce comfort, interfere with daily routines, or be technically impractical. Therefore, excessive tariff volatility can create incentives that are difficult to follow in practice, even when automation is available. This implies that a consumer-oriented tariff mechanism should not only provide a clear price signal, but should also limit unnecessary short-term fluctuations to keep demand response practical and acceptable.

4.3.4 CSP perspective

From the CSP perspective, dynamic grid tariffs represent both an opportunity and a risk. While price variation enables value creation through flexibility, excessive volatility and uncertainty undermine the

stability of their business case. CSPs emphasise the importance of predictable and timely tariff signals, as well as access to accurate data and sufficient aggregation scale. In addition, uncertainty regarding future market roles and coordination with other actors highlights the need for clear responsibilities and financially viable incentives.

4.3.5 BRP perspective

For BRPs, the primary concern is the interaction between dynamic grid tariffs and balancing markets. Changes in consumer behaviour driven by tariff signals introduce uncertainty in demand patterns, increasing imbalance risks. This issue is particularly relevant when tariff incentives conflict with wholesale or balancing signals. Such misalignment increases forecast errors and complicates system balancing, emphasising the importance of signal coordination and predictability. Lastly, BRPs expressed concerns about the role of CSPs and other flexibility-steering parties in influencing demand within BRP portfolios. If these parties adjust consumption patterns without sufficient coordination, the predictability of demand behaviour within BRP portfolios may decrease. This can increase imbalance risks and associated costs for BRPs. Therefore, the mechanism should include a clear delineation of market roles and responsibilities, ensuring that flexibility activation does not create unintended risks for actors responsible for portfolio balance.

4.3.6 Aggregator perspective

The interview findings from the aggregator perspective highlighted that aggregation of household flexibility is technically possible, but requires a high degree of automation. Individual consumers cannot realistically be expected to continuously respond to changing tariff signals, meaning that automated coordination of flexible assets, for example through a HEMS, is considered essential.
A key concern raised in the interviews was the reliability of the required communication and control infrastructure. Large-scale aggregation requires different systems and assets to communicate continuously, while failures may create financial risks when flexibility is not activated as expected. This also raises questions regarding the allocation of responsibilities for communication, system operation, maintenance, and asset control. Clear role allocation and reliable technical infrastructure are therefore important conditions for scalable household aggregation.

Building on the actor analysis, which identified consumer complexity and the need for limited active involvement as important concerns, the aggregator interview indicated that this may also create an opportunity for aggregators. By acting as an intermediary, an aggregator could translate complex and frequently changing tariff signals into automated optimisation decisions on behalf of consumers. At the same time, coordinating flexibility across a sufficiently large portfolio may allow individual deviations to partly offset each other and can improve the manageability of flexibility and financial risk. Capacity-based steering contracts may further increase certainty regarding the flexibility available during congestion periods. The interview therefore suggests that aggregators could play a dual role: reducing the complexity faced by consumers while coordinating flexibility and associated risks at portfolio level.

4.4 Key cross-actor insights

The actor analysis reveals several recurring themes that cut across individual actor perspectives. These themes capture the main stakes, constraints, and opportunities that should be considered in the design of dynamic grid tariffs.

First, price volatility, predictability, and risk allocation are important concerns across multiple actors. Consumers aim to limit exposure to unexpected tariff costs, while suppliers and BRPs face financial risks related to bill volatility, forecasting uncertainty, and imbalance exposure. At the same time, dynamic tariffs may provide stronger congestion-related incentives. This creates a trade-off between maintaining an effective congestion signal and limiting the financial uncertainty imposed on grid users and market parties.

Second, system complexity and implementation feasibility form an important constraint. Consumers generally require tariff structures that are understandable and do not require continuous active response,

while suppliers may need to adapt billing, IT, and communication systems. Consumer heterogeneity further complicates this issue, since households differ considerably in their ability to understand and respond to dynamic tariff signals and in their access to flexible technologies. A mechanism should therefore be practically implementable while remaining accessible to consumers with different levels of flexibility and technical capability.

Third, coordination between dynamic grid tariffs and existing electricity-market signals is important. Consumers and flexible assets may simultaneously respond to electricity prices, grid tariffs, balancing incentives, and revenues from flexibility services. These signals may not always provide incentives in the same direction, potentially creating uncertainty for BRPs, suppliers, CSPs, and aggregators. Predictable and timely tariff information and sufficient coordination with existing market structures are therefore important conditions for implementation.

Fourth, the introduction of dynamic grid tariffs may create opportunities for market parties as well as additional burdens. Suppliers, CSPs, and aggregators already operate in markets characterised by changing price signals, short decision horizons, and frequent optimisation. These capabilities may allow them to incorporate congestion-related grid tariffs into existing optimisation and flexibility services. Aggregators and other energy service providers may, for example, manage flexible assets on behalf of consumers and thereby reduce the need for households to continuously interpret and respond to complex tariff signals themselves. At the same time, such roles require a viable business case and may introduce additional operational, technical, and coordination responsibilities. Dynamic grid tariffs should therefore be assessed not only in terms of the burdens they impose on market parties, but also in terms of the opportunities they create for new or expanded services.

Finally, role allocation and market-design uncertainty remain important institutional concerns. The introduction of new tariff and flexibility services may create overlap between the activities of suppliers, CSPs, aggregators, and other flexibility providers. Unclear responsibilities regarding tariff information, flexibility control, settlement, data exchange, and risk allocation may increase operational uncertainty and hinder implementation. Clear delineation of actor roles and responsibilities is therefore required for a coherent and scalable market design.

Together, these findings show that dynamic grid tariffs cannot be assessed solely based on their ability to provide congestion-reducing incentives. Their effects on financial risk, complexity, consumer heterogeneity, market coordination, business opportunities, implementation burdens, and actor responsibilities must also be considered. These cross-actor insights provide the basis for the design criteria developed in the following chapter.

The actor-specific findings underlying this synthesis are summarised in Table 5.

Table 5: Synthesis of actor stakes, constraints, instruments, and requirements

Actor	Stakes / objectives	Constraints	Instruments	Requirements
Supplier	• Low implementation costs • Limited operational burden • Stable and predictable business operations	• Limited influence over grid tariff design • Adaptation of billing and IT systems	• Contract design • Billing systems • Consumer communication	• Predictable tariffs • Reliable tariff information • Manageable implementation burden
Consumer	• Affordable electricity costs • Low complexity • Maintaining comfort • Limited tariff volatility	• Limited flexibility • Limited knowledge • Limited time for active response	• Demand shifting or reduction • Investment in flexible assets • Automation through HEMS	• Limited cost exposure • Simple tariff logic • Clear purpose • Limited required actions
DSO (Stedin)	• Grid congestion reduction • Reliable grid operation • Lower network costs • Market adoption	• Regulatory constraints • Dependence on market response • No direct control over household demand	• Tariff design • Network monitoring and data • Definition of congestion signals	• Effective congestion signal • Regulatory compliance • Technical feasibility • Market acceptance
CSP	• Viable flexibility services • Effective use of flexibility • Stable business case	• Exposure to forecast errors • Dependence on controllable assets • Dependence on reliable information	• Activation of flexibility • Coordination of flexible assets • Participation in flexibility markets	• Accurate and timely information • Financially viable incentives • Clear market roles
BRP	• Limited imbalance exposure • Predictable portfolio demand • Alignment with balancing signals	• Exposure to forecast errors • Consumer response outside direct control • Limited influence over grid tariff signals	• Portfolio forecasting • Portfolio optimisation and market adjustment • Contractual risk pricing	• Limited imbalance exposure • Predictable tariff information • Alignment with balancing signals • Clear actor responsibilities
Aggregator	• Viable long-term business case • Efficient coordination of flexibility • Manageable portfolio risk	• Communication and control reliability • Dependence on access to flexible assets • Uncertainty regarding responsibilities	• Aggregation and coordination of flexibility • Automated asset control • Portfolio risk pooling • Contractual risk management	• Accurate and timely information • Reliable communication infrastructure • Clear role allocation • Financially viable incentives

5 Design criteria

This chapter translates the main actor goals and requirements identified in the actor analysis into a set of design criteria. These criteria provide a structured basis for assessing the performance of alternative grid-tariff mechanisms and for comparing the extent to which they address the interests of the involved actors.
The criteria are derived by combining findings from the literature review with insights from the stakeholder interviews. Existing criteria from previous tariff design studies provide the theoretical foundation, while the interview findings are used to verify, refine, and complement this set for the specific context of dynamic grid tariffs.

5.1 From actor analysis to design criteria

The actor analysis identified the stakes, constraints, and preliminary requirements of the actors involved in dynamic grid tariffs. These findings provide an actor-specific perspective on what the tariff mechanism should achieve and which adverse effects should be avoided. To translate these findings into a structured set of design criteria, they are combined with the tariff evaluation frameworks identified in the literature review.

Four complementary literature sources form the basis for this translation. First, the four evaluation dimensions of Christensen et al. (2021), defined as technical, economic, social, and regulatory feasibility, are used as an overarching structure for categorising the actor requirements. Second, the five tariff objectives identified by Hennig et al. (2022), namely cost recovery, cost reflectiveness, non-discrimination, cost efficiency, and simplicity, provide existing criteria against which the actor requirements can be compared. Third, Abdelmotteleb et al. (2017) provide additional criteria related particularly to network performance and consumer response, including network cost recovery, savings in required network reinforcements, efficient consumer response, and recognition of side-effects on consumers. Finally, Wang et al. (2023) complement these frameworks with principles particularly relevant to dynamic network tariffs, including additivity, practical implementation, intelligibility, and the technical prerequisites required for their implementation.
The development of the design criteria follows two steps. First, the requirements identified in the actor analysis are categorised according to the four evaluation dimensions of Christensen et al. (2021). This provides insight into whether the identified concerns are primarily technical, economic, social, or regulatory in nature, and allows similarities and conflicts between actors to be identified within a common structure.
Second, the actor requirements are translated into specific design criteria. For this purpose, each requirement is compared with the existing criteria and principles identified by Hennig et al. (2022), Abdelmotteleb et al. (2017), and Wang et al. (2023). Where an actor requirement is sufficiently represented by an existing criterion, this criterion is adopted or adapted to the specific context of this research. Where the existing literature does not adequately capture an actor requirement, an additional criterion is introduced. The resulting set of design criteria is therefore grounded in existing tariff evaluation literature while remaining responsive to the actor-specific requirements identified for dynamic grid tariffs in this research.

5.2 Defining the criteria set

In the remainder of this chapter, the criteria and principles identified by Hennig et al. (2022), Abdelmotteleb et al. (2017), and Wang et al. (2023) are collectively referred to as the literature-based criteria.

Supplier

For suppliers, the main goals are low implementation costs, limited additional burdens, and stable and predictable business operations. These goals mainly fall within the economic feasibility dimension of Christensen et al. (2021), as additional system changes, responsibilities, and operational tasks may require investments and increase financial or organisational risks.

Several of these goals are already reflected in the literature-based criteria. Low implementation costs are captured by simplicity and practical implementation. However, recurring operational burdens are not fully captured by these criteria. The interviews show that the relevance of such burdens differs between supplier types. Traditional suppliers generally prefer limited additional responsibilities, whereas more flex-oriented suppliers may be willing to take on additional tasks when these create opportunities for new services or revenues. Therefore, limited additional burden is retained as a separate criterion.

Suppliers also require accurate and timely tariff information and sufficient tariff predictability. These requirements are only partly captured by the literature-based criteria. Reliable tariff information is necessary for forecasting, portfolio management, and consumer communication, while predictable tariffs help suppliers anticipate tariff developments and manage associated risks. Therefore, accurate and timely tariff information and predictable tariffs are included as additional criteria.

Based on this translation, the supplier perspective results in the following criteria:

- Limited additional burden
- Simplicity of implementation
- Accurate and timely tariff information
- Predictable tariffs

Consumer
For consumers, the main goals are low electricity costs, low complexity, a clear purpose of the mechanism, limited required actions, and low tariff volatility. These goals relate to several dimensions identified by Christensen et al. (2021). Low electricity costs fall within the economic feasibility dimension, as they directly concern the financial impact of dynamic grid tariffs on households. A clear purpose is mainly related to social feasibility, because consumers are more likely to accept a new tariff mechanism when they understand why it is introduced and how it contributes to reducing grid congestion. Low complexity and limited required actions relate to both social and technical feasibility, as the mechanism should be understandable and practically usable for different types of consumers. Low tariff volatility also relates to both social and technical feasibility, since frequent tariff changes may increase financial uncertainty and make it more difficult for consumers to respond effectively.

The importance of limited required actions differs between consumer groups. Some consumers may not want to actively respond to price signals or adjust their electricity use throughout the day, while others may have both the motivation and technical means, such as electric vehicles, heat pumps, or home batteries, to contribute to congestion reduction. Due to this heterogeneity, mechanisms requiring fewer active consumer actions are generally more accessible to a broader group of households.

The literature-based criteria partly capture these consumer requirements. The recognition of side-effects on consumers identified by Abdelmotteleb et al. (2017) provides a basis for considering adverse financial consequences. In this research, this is translated into low consumer cost exposure, which captures the extent to which consumers are exposed to high or uncertain tariff costs.

Consumer complexity is partly captured by the principle of intelligibility identified by Wang et al. (2023), which concerns whether consumers understand how tariff costs are determined and how their behaviour affects these costs. This principle is broadened into simplicity of adaptation, which also considers the effort required for consumers to respond to the mechanism. Limited required actions are therefore covered by the same criterion.

The goal of a clear purpose is only partly captured by intelligibility. In addition to understanding how tariff costs are determined, consumers should understand why the tariff mechanism is introduced and how their behaviour relates to grid congestion. Therefore, clear purpose of the new system is included as an additional criterion. Finally, low tariff volatility is added because excessive tariff variation may increase financial uncertainty and reduce the practical usability of the tariff signal for consumers.

Based on this translation, the consumer perspective results in the following criteria:

- Low consumer cost exposure
- Simplicity of adaptation
- Clear purpose of the new system
- Low tariff volatility

Stedin
For Stedin, the main goals are effective peak shaving, lower network costs, sufficient cost recovery, and market adoption. These goals follow directly from its role as a distribution system operator, as the mechanism should reduce grid congestion, limit the need for grid reinforcement, maintain sufficient network revenues, and be feasible for implementation in practice.

Effective peak shaving primarily relates to the technical feasibility dimension of Christensen et al. (2021), as the tariff mechanism should create a response during congested periods. However, its effectiveness also depends on sufficient economic incentives and the willingness and ability of consumers and market parties to respond. Lower network costs and cost recovery primarily fall within the economic feasibility dimension. Reducing congestion may improve the utilisation of existing grid capacity and potentially reduce the need for costly grid reinforcement, which is captured by cost efficiency. Cost recovery is already included in the literature-based criteria and captures whether sufficient network tariff revenues are maintained.
In addition, an effective congestion signal should reflect the intensity of local grid congestion. This aspect is captured by the criterion *congestion reflectiveness*, which assesses the extent to which tariff levels correspond with changing congestion conditions. This differs from *grid congestion reduction*: congestion reflectiveness concerns the quality of the tariff signal itself, whereas grid congestion reduction concerns the resulting effect on network loading.
Cost recovery should not be considered independently from the wider system effects of the mechanism. Lower tariff revenues may coincide with stronger flexibility incentives and reduced congestion, which can create value through improved utilisation of existing grid capacity. These effects are therefore considered separately through cost efficiency and congestion reduction.
Market adoption relates to all four feasibility dimensions. The literature-based criteria partly capture this through simplicity and practical implementation, as well as through efficient consumer response. However, successful adoption also requires sufficient financial incentives to participate and respond to the tariff signal. Therefore, economic incentives are included as an additional criterion to capture whether the mechanism financially rewards participation and congestion-responsive flexibility.

Finally, effective peak shaving is only partly represented by existing criteria such as efficient consumer response. Since congestion reduction is a central objective of the tariff mechanism, grid congestion reduction is included as a separate criterion. Together, cost recovery, cost efficiency, economic incentives, and grid congestion reduction capture the main objectives identified from the Stedin perspective.

Based on this translation, the Stedin perspective results in the following criteria:

- Congestion reflectiveness
- Grid congestion reduction
- Cost efficiency
- Economic incentives
- Cost recovery

CSP

For CSPs, the main goals are accurate and timely tariff information, cost efficiency, and sufficient economic incentives. These goals mainly relate to the technical and economic feasibility dimensions identified by Christensen et al. (2021). Reliable tariff information is primarily a technical requirement, as CSPs depend on timely and sufficiently detailed information to optimise and steer flexible assets. Cost efficiency and economic incentives mainly relate to economic feasibility, since participation should remain affordable while creating sufficient value for flexibility services.

The literature-based criteria partly capture these requirements. Cost efficiency is already explicitly included, while efficient consumer response partly reflects the need for appropriate financial incentives. From the CSP perspective, however, the mechanism should also create sufficient value to support flexibility services and automated optimisation. Economic incentives are therefore retained as a separate criterion.
Accurate and timely tariff information is also partly reflected in the technical prerequisites and implementation principles identified in the literature, but its importance is particularly emphasised by the CSP perspective. Reliable and timely tariff information is therefore included as a separate criterion, referring to whether CSPs receive the information required to operate and optimise flexibility effectively.

Based on this translation, the CSP perspective results in the following criteria:

- Accurate and timely tariff information
- Cost efficiency
- Economic incentives

BRP
For BRPs, the main goals are limited interference with other electricity-market signals, limited imbalance exposure, predictable demand, and clear delineation of market roles. These goals mainly relate to the technical, economic, and regulatory feasibility dimensions identified by Christensen et al. (2021).

Interaction with other electricity-market signals is relevant from both a technical and economic perspective. If dynamic grid tariff signals conflict with wholesale or balancing-market incentives, consumer behaviour may become more difficult to forecast and BRPs may face greater imbalance exposure and associated costs. Predictable tariff signals are therefore also important, as they help BRPs anticipate changes in consumer demand and reduce uncertainty in portfolio management. Clear market role delineation mainly relates to regulatory feasibility, since unclear responsibilities may increase coordination problems and uncertainty regarding responsibility allocation.

The literature-based criteria partly capture these requirements. In particular, Wang et al. (2023) identify additivity as an important principle, referring to the compatibility of network tariffs with other market price signals. In this research, this principle is translated into the criterion interaction with other electricity-market signals.

Ideally, this criterion would consider both wholesale-market and balancing-market signals. However, balancing prices and BRP portfolio positions are not represented in the simulation model. Its quantitative operationalisation is therefore limited to the interaction between the grid tariff and the dynamic electricity price, as explained in Section 5.5.3.
Limited imbalance exposure is not included as a separate criterion, as it is treated as a consequence of tariff predictability and the interaction with other electricity-market signals. Predictable demand is similarly represented through the criterion predictable tariffs. Finally, clear delineation of actor roles is included as an additional criterion because unclear responsibilities may increase operational and coordination uncertainty.

Based on this translation, the BRP perspective results in the following criteria:

- Interaction with other electricity-market signals

- Predictable tariffs
- Clear delineation of actor roles

Aggregator
The actor analysis identifies four main requirements from the aggregator perspective: accurate and timely tariff information, a viable long-term business case, reliable communication and automation infrastructure, and clear allocation of roles and responsibilities. Following the dimensions of Christensen et al. (2021), information provision and communication infrastructure primarily relate to technical feasibility, the long-term business case to economic feasibility, and role allocation to regulatory feasibility.

The literature-based criteria partly capture these requirements. Accurate and timely tariff information is related to the technical and implementation requirements identified in the literature, while economic incentives capture whether sufficient financial value exists to support the coordination of flexibility. Clear allocation of roles and responsibilities is less explicitly represented and is therefore included as an additional criterion.

Based on these requirements, three criteria are retained:

- Accurate and timely tariff information
- Economic incentives
- Clear delineation of actor roles

Reliable communication and automation infrastructure is considered an important prerequisite for the successful aggregation of household flexibility, but is not included as a separate evaluation criterion because it is required for the functioning of aggregation rather than representing a characteristic on which the proposed mechanisms are compared.

5.3 Overview of criteria

The actor-specific translation of goals and requirements results in a preliminary set of design criteria. These criteria build on the literature-based framework and are adopted, adapted, or complemented where necessary based on the actor analysis.

Several criteria are adopted directly from the literature: cost recovery, cost reflectiveness, non-discrimination, cost efficiency, and simplicity of implementation. Other literature-based principles are adapted to the context of this research. Recognition of side-effects on consumers is translated into low consumer cost exposure, intelligibility is broadened into simplicity of adaptation, and additivity is translated into interaction with other electricity-market signals.
Additional criteria follow from actor-specific requirements that are not fully captured by the literature-based framework. These include limited additional burden, predictable tariffs, accurate and timely tariff information, clear purpose of the new system, and clear delineation of actor roles.

From the system perspective, congestion reflectiveness and grid congestion reduction are added because congestion management is a central objective of the tariff mechanism. Congestion reflectiveness assesses whether tariff levels correspond with the intensity of local grid congestion, whereas grid congestion reduction concerns the resulting effect on network loading. This differs from cost reflectiveness, which concerns whether tariff charges reflect the network costs caused by individual users. Economic incentives are also included to assess whether the mechanism financially rewards flexible and congestion-responsive behaviour.

The resulting preliminary criteria therefore combine established tariff-evaluation principles with actor-specific requirements relevant to dynamic grid tariffs. The following section assesses which criteria can be retained within the scope of this research and how they can be operationalised consistently.

5.4 Selection of criteria

The criteria presented in section 5.3 result in a set of 16 candidate criteria. To keep the evaluation focused and avoid overlap, the final criteria are selected based on the research scope, overlap between criteria, and the capabilities of the evaluation model. The following criteria are not retained as separate evaluation criteria:

- *Cost efficiency* is excluded because the model does not quantify system-wide costs and benefits, such as congestion-management costs or avoided grid-reinforcement investments.
- *Predictable tariffs* is excluded because the model uses a fixed annual network-loading profile and does not represent uncertainty in future congestion conditions or tariff forecasts. In addition, the announcement horizon is already captured by the *time horizon* design variable.
- *Simplicity of adaptation* is not retained separately because its main components overlap with other criteria. The effort required from consumers is captured by *limited additional burden*, while tariff comprehensibility is assessed through *clear purpose of the new system*.
- *Cost reflectiveness* is excluded because the available data do not allow the contribution of individual consumers to network costs to be determined. This is distinct from *congestion reflectiveness*, which is retained to assess how closely tariff levels correspond with local congestion intensity.
- *Accurate and timely tariff information* is treated as a prerequisite rather than a performance criterion. Accurate information is required for all mechanisms to function correctly, while differences in communication timing are captured through the *time horizon* design variable.
- *Grid congestion reduction* is not retained as a separate criterion because the tariff simulation model does not recalculate network loading after consumer flexibility is activated and therefore cannot determine realised physical congestion reduction. Instead, congestion-reduction potential is represented by the tariff-related flexibility benefit and incorporated as a sub-indicator of *economic incentives*.

The timing of tariff information does differ between mechanisms, but this aspect is already explicitly represented by the *time horizon* design variable. The mechanisms therefore differ in whether tariff information is determined and communicated in real time, day-ahead, monthly, or yearly. Retaining timely information as a separate evaluation criterion would consequently assess the same design characteristic twice. For this reason, accurate tariff information is treated as a minimum design requirement, while differences in information timing are captured through the time-horizon design variable.

5.5 Operationalising the criteria

To enable a consistent evaluation of the alternative tariff systems, the selected criteria are operationalised. This process specifies at which level each criterion is evaluated, how its performance is assessed, and which metric or assessment method is used.

The operationalisation consists of three steps. First, the criteria are classified according to their evaluation level as system-level, actor-level, or both. Second, the appropriate evaluation method is determined by distinguishing between quantitative and qualitative criteria. Finally, each criterion is translated into a measurable indicator or predefined qualitative assessment method, including the corresponding unit or assessment scale.

5.5.1 Classification by evaluation level

The criteria are first classified according to the level at which their performance is evaluated. This classification is based on the unit of evaluation rather than on the actor from which the criterion was originally derived. The following decision rules are applied:

- A criterion is classified as *system-level* when its performance describes a property or outcome of the tariff mechanism or electricity system as a whole and can be evaluated independently of a specific actor.

- A criterion is classified as *actor-level* when its performance depends on the position, costs, capabilities, responsibilities, or risks of a specific actor or actor group.
- A criterion is classified as *system/actor-level* when it has both a system-wide effect and a directly distinguishable effect on one or more individual actors.

This distinction is applied based on the object whose performance is measured. The origin of a criterion in the actor analysis does not determine its classification. For example, tariff volatility was identified as an important concern for consumers, but the volatility itself is a characteristic of the tariff signal and is therefore evaluated at the system level. Consumer-specific financial consequences of this volatility are captured separately through consumer cost exposure.

To structure the evaluation framework, the criteria are classified according to the level at which they primarily apply. Some criteria describe properties or outcomes of the tariff mechanism at the system level, such as tariff volatility and tariff reflectiveness. These criteria can be evaluated independently of the position of a specific actor.
Other criteria apply primarily at the actor level, such as low consumer cost exposure, simplicity of implementation, limited additional burdens, and clear purpose of the new system. These criteria assess how the mechanism affects the costs, responsibilities, or practical feasibility experienced by specific actors.
Finally, some criteria apply to both the system and actor level. Economic incentives are classified as a system/actor-level criterion because they capture the financial incentives experienced by consumers, while the congestion-related component of these incentives is also used to assess the potential contribution to congestion-reducing behaviour. Cost recovery similarly concerns the financial position of the DSO while also representing a system-level requirement for maintaining sufficient network revenues. The interaction with other electricity-market signals is also classified at both levels, as the interaction between price signals influences the overall coordination of flexible demand while simultaneously affecting the incentives faced by consumers and market parties.

This classification distinguishes system performance from actor-specific effects while making explicit where both perspectives overlap. Table 6 provides an overview of the selected criteria and their evaluation level.

Table 6: Classification of final criteria by evaluation level

Criterion	Classification rationale
System-level criteria	
Low tariff volatility	Describes the variability of the tariff signal itself and can be assessed independently of individual actor responses.
Congestion reflectiveness	Assesses the extent to which tariff levels reflect the intensity of local grid congestion.
Delineation of actor roles	Concerns the institutional structure of the mechanism and whether responsibilities and interactions between actors are clearly defined.
Actor-level criteria	
Simplicity of implementation	Depends on the technical and organisational changes required from the actors responsible for implementing the mechanism.
Limited additional burdens	Concerns additional tasks, responsibilities, or operational risks imposed on specific market actors.
Low consumer cost exposure	Directly concerns the financial consequences of the mechanism for individual consumers or consumer profiles.
Clear purpose of the new system	Concerns whether consumers and market actors can understand the purpose and functioning of the mechanism.
System/actor-level criteria	
Cost recovery	Concerns the recovery of network tariff revenues, while the financial consequences of insufficient recovery primarily affect the DSO.
Non-discrimination	Represents a system-wide regulatory principle, while its consequences can be assessed by comparing the treatment of specific users or actor groups.
Economic incentives	Concerns the financial incentives faced by consumers to activate or adopt flexibility, while the congestion-related component also indicates the potential contribution to congestion reduction.
Interaction with other electricity-market signals	Concerns the interaction between grid tariffs and other market price signals, while conflicting incentives may affect consumers and market parties such as BRPs.

Table 6 distinguishes between system-level, actor-level, and combined system/actor-level criteria. This distinction reflects the aim of evaluating both the overall performance of the tariff mechanism and its consequences for individual actors. A mechanism may perform well from a system perspective while creating undesirable effects for specific actors, or vice versa. Including both perspectives therefore makes these trade-offs explicit.

The classification is based on the level at which a criterion is evaluated rather than on the actor from which it originates. For example, low tariff volatility originates primarily from consumer concerns, but volatility itself is a characteristic of the tariff signal and is therefore classified at system level. Similarly, interaction with other electricity-market signals follows primarily from the BRP perspective, but affects both wider system coordination and the risks faced by individual market actors, and is therefore classified at system/actor level. This illustrates the interdependence between actor interests and system performance.

5.5.2 Quantitative and qualitative evaluation

The next step determines how the performance of each criterion is evaluated. To make this classification reproducible, the same decision rules are applied to all criteria. The classification is based on whether the criterion can be represented by an observable and consistently calculable outcome within the scope of the available data and simulation model.

A criterion is classified as *quantitative* when its performance can be expressed numerically using available model outputs or input data, and when the same calculation procedure can be applied consistently to all mechanism designs.

A criterion is classified as *qualitative* when its performance depends primarily on institutional, organisational, behavioural, or implementation characteristics that are not represented numerically in the simulation model. These criteria are assessed using predefined qualitative assessment rules.

A criterion is classified as *quantitative/qualitative* when a numerical indicator captures part of the criterion, but additional interpretation is required to assess aspects that fall outside the scope of the model. In these cases, the quantitative result supports, but does not independently determine, the final assessment.

The following decision sequence is therefore applied to each criterion:

1. Determine whether an observable numerical outcome exists within the available data or simulation model.
2. Determine whether this outcome fully covers the meaning of the criterion.
3. If both conditions are satisfied, the criterion is classified as quantitative.
4. If no suitable numerical outcome is available, the criterion is classified as qualitative.
5. If a numerical outcome captures only part of the criterion, the criterion is classified as quantitative/qualitative.

This classification ensures that criteria are only quantified where the available data and model provide a meaningful numerical representation. It also avoids assigning numerical values to criteria for which such precision would not be justified.

Table 7: Classification of final design criteria by evaluation method

Evaluation method	**Design criteria**
Quantitative	Cost recovery; Low consumer cost exposure; Low tariff volatility; Congestion reflectiveness; Economic incentives; Interaction with other electricity-market signals
Qualitative	Simplicity of implementation; Limited additional burdens; Clear purpose of the new system; Delineation of actor roles; Non-discrimination

Most criteria can be classified directly using the decision rules above. However, the criterion *economic incentives* requires additional explanation because it combines three complementary sub-indicators.

First, potential flexibility benefits measure the financial value that consumers can obtain by operating flexible assets in response to the applicable price signals. Second, congestion-reduction potential focuses specifically on the part of this benefit attributable to the grid tariff. Since the model does not recalculate physical network loading after flexibility activation, the tariff-related flexibility benefit represents the strength of the financial incentive for congestion-responsive behaviour rather than realised congestion reduction. Third, the incentive of asset ownership assesses whether the tariff mechanism changes the effective tariff burden of household profiles with different energy assets.

Combining these three perspectives within one criterion captures both the consumer-level financial incentives and their relevance to the system objective of congestion reduction, while avoiding overlap between separate evaluation criteria.

5.5.3 Defining quantitative indicators and units

For each criterion with a quantitative component, a measurable indicator and corresponding unit are defined. The purpose of this step is to translate the abstract criteria into quantities that can be calculated consistently for each tariff mechanism. The unit is not selected independently, but follows from the aspect of performance represented by the criterion and the calculation used to measure it. For each quantitative criterion, the operationalisation therefore specifies (1) the quantity that is measured, (2) the calculation method, (3) the data over which the calculation is performed,

(4) the resulting unit, and (5) how the resulting value should be interpreted. This ensures that the same procedure can be applied to all mechanism designs and that the resulting scores can be reproduced.

Consumer cost exposure, cost recovery, and flexibility benefits are evaluated on an annual basis in €/year. A full-year evaluation is used because electricity consumption, generation, flexibility, market prices, and grid congestion vary substantially across seasons. For example, PV generation is concentrated in summer, while heat-pump demand and consumption-related congestion are generally higher in winter. Evaluating these effects over a full year therefore captures seasonal variation and prevents the results from being disproportionately influenced by a particular month or season. It also aligns with the annual perspective commonly used for household electricity costs and grid-tariff revenues.

Where the magnitude of a change relative to a reference situation is relevant, percentages are reported in addition to absolute monetary values. Relative measures allow mechanisms to be compared independently of differences in the absolute cost or revenue level of the underlying consumer profile. For economic incentives, tariff costs are additionally normalised by annual imported electricity and expressed in €/kWh. This allows the effective tariff burden to be compared across household profiles with different levels of electricity consumption. The indicator is used to examine whether household configurations with greater opportunities for flexible electricity use face systematically different tariff costs per unit of imported electricity.

Criteria that describe the relationship between two time series are evaluated using dimensionless correlation coefficients. Pearson's correlation coefficient is used for tariff congestion reflectiveness because the objective is to assess the strength and direction of the relationship between the signals rather than their absolute magnitude. Using a dimensionless measure also allows variables expressed in different physical or monetary units to be compared.

Congestion reflectiveness is measured using the Pearson correlation coefficient between the hourly grid tariff and the congestion-intensity indicator. A higher positive correlation indicates a stronger linear correspondence between tariff levels and congestion intensity. This indicator measures how closely the tariff signal reflects congestion conditions, rather than the magnitude of the financial incentive or the realised reduction in congestion.

The criterion *interaction with other electricity-market signals* is operationalised using the interaction between the grid tariff and the dynamic electricity price. The electricity price is selected because it represents a relevant hourly price signal faced by consumers with dynamic contracts and is available at the same resolution as the grid tariff. Balancing-market signals and BRP portfolio positions are outside the scope of the simulation model. The indicator should therefore be interpreted as a partial assessment of interaction with electricity-market signals rather than a complete representation of all relevant market interactions.

The annual mean of each signal is used as the reference level because the purpose of the indicator is to compare the direction of the incentives rather than their absolute magnitude. The grid tariff and electricity price have different price levels and distributions and therefore cannot be compared directly. Expressing each hourly value relative to its own annual mean provides a common reference: values above the annual mean represent relatively expensive hours and therefore a discouraging signal for electricity consumption, while values below the mean represent relatively inexpensive hours and therefore an encouraging signal. Using a fixed annual reference ensures that the same classification rule is applied consistently across the entire simulation period.
Based on this classification, the signals are considered aligned when both are above their respective annual means or both are below their respective annual means. They are considered conflicting when one signal is above its mean while the other is below its mean. The resulting shares of aligned and conflicting hours are reported as percentages of the simulation period. Neither outcome is assumed to be inherently preferable; the indicator is used descriptively to identify the extent to which the two price signals reinforce or oppose each other. The annual mean is used solely as a consistent analytical reference and should not be interpreted as a behavioural threshold at which consumers necessarily change their electricity use.

Tariff volatility is evaluated using both the standard deviation and the coefficient of variation (CoV).

The standard deviation expresses the absolute tariff variation in €/kWh, while the CoV expresses this variation relative to the mean tariff level. Because the evaluated mechanisms can have different average tariff levels, the CoV is used as the main comparative measure, as it allows the relative volatility of tariffs with different mean levels to be compared consistently. The indicator measures the volatility of the underlying tariff signal, rather than the consumer's effective exposure to this volatility. Subscription-based mechanisms can therefore retain the same volatile tariff signal while shielding part of consumption from its financial effects. This distinction is considered when interpreting the results. Tables 8 and 9 present the formulas, quantities, and units used for the quantitative indicators.

The criterion *economic incentives* is evaluated through three complementary sub-indicators: potential flexibility benefits, congestion-reduction potential, and the incentive of asset ownership.

1

First, potential flexibility benefits measure the financial value that consumers can obtain by adapting the operation of flexible assets. The total flexibility benefit, $B_{\text{total},i}$, captures the change in total electricity costs resulting from flexible operation, while $B_{\text{tariff},i}$ isolates the part of this benefit attributable specifically to the grid tariff.

2

Second, congestion-reduction potential is evaluated using the same tariff-related flexibility benefit, $B_{\text{tariff},i}$, but with a different interpretation. A positive tariff-related benefit indicates that the flexible operating schedule reduces grid-tariff costs relative to the original schedule and therefore that the tariff provides a financial incentive consistent with congestion-responsive operation. A higher positive value represents a stronger congestion-related financial incentive. Since network loading is not recalculated after flexibility activation, this indicator represents congestion-reduction potential rather than realised physical congestion reduction.

3

Third, the incentive of asset ownership is evaluated using the effective grid-tariff burden per imported kWh, $T^{\text{eff}}_{i,m}$. This normalises annual tariff costs by imported electricity and allows the tariff treatment of household profiles with different combinations of energy assets to be compared. A lower effective tariff burden for a profile containing an EV, heat pump, battery, or PV system indicates that the grid tariff improves the tariff-based economic attractiveness of using such an asset. For example, lower electricity-related tariff costs for an EV or heat pump can improve their operating-cost position relative to conventional alternatives such as a petrol vehicle or gas-based heating. The indicator therefore captures whether the grid tariff creates an additional financial incentive for asset ownership through electricity-use costs.
It does not, however, represent the full economic attractiveness or investment case of these technologies, as purchase costs, maintenance costs, fuel or gas costs, subsidies, and other technology-specific costs are outside the scope of the analysis.

Table 8: Overview of quantitative indicators, formulas, and units (1/2)

Criterion	**Formula**	**Quantities**	**Unit / interpretation**
Cost recovery	$\Delta R_m = R_m - R_{\text{ref}}$ $\Delta R_{m,\%} = \frac{R_m - R_{\text{ref}}}{R_{\text{ref}}} \times 100\%$	R_m = annual tariff revenue under mechanism m [€/year] R_{ref} = annual tariff revenue under the static reference tariff [€/year] ΔR_m = difference in annual tariff revenue	€/year and % Closer to zero indicates revenue closer to the reference case.
Consumer cost exposure	$\Delta C_{i,m} = C_{i,m} - C_{i,\text{ref}}$ $\Delta C_{i,m,\%} = \frac{C_{i,m} - C_{i,\text{ref}}}{C_{i,\text{ref}}} \times 100\%$	$C_{i,m}$ = annual costs of consumer profile i under mechanism m [€/year] $C_{i,\text{ref}}$ = annual costs under the static reference tariff [€/year]	€/year and % Positive values indicate higher costs than the reference case.
Tariff volatility	$\mu_T = \frac{1}{N}\sum_{t=1}^{N} T_t$ $\sigma_T = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(T_t - \mu_T)^2}$ $\text{CoV} = \frac{\sigma_T}{\mu_T}$	T_t = tariff at hour t [€/kWh] μ_T = mean hourly tariff [€/kWh] σ_T = standard deviation [€/kWh] N = number of hourly observations	σ_T: €/kWh CoV: dimensionless [-] Higher CoV indicates greater relative volatility.
Tariff reflectiveness	$r_{T,G} = \frac{\sum_{t=1}^{N}(T_t - \bar{T})(G_t - \bar{G})}{\sqrt{\sum_{t=1}^{N}(T_t - \bar{T})^2 \sum_{t=1}^{N}(G_t - \bar{G})^2}}$	T_t = tariff at hour t [€/kWh] G_t = congestion indicator at hour t $\bar{T}$ = mean tariff $\bar{G}$ = mean congestion indicator	Pearson r [-] Values closer to +1 indicate stronger tariff reflectiveness.

Table 9: Overview of quantitative indicators, formulas, and units (2/2)

Criterion	**Formula**	**Quantities**	**Unit / interpretation**
Economic incentives	Potential flexibility benefits: $B_{\text{total},i} = C_{\text{original},i} - C_{\text{flexible},i}$ $B_{\text{tariff},i} = C_{\text{tariff,original},i} - C_{\text{tariff,flexible},i}$ Incentive of asset ownership: $T^{\text{eff}}_{i,m} = \frac{C_{\text{tariff},i,m}}{E_{\text{import},i,m}}$ $\Delta T^{\text{eff}}_{i,m} = T^{\text{eff}}_{i,m} - T^{\text{eff}}_{i,\text{ref}}$	$B_{\text{total},i}$ = total annual flexibility benefit of profile i [€/year] $B_{\text{tariff},i}$ = annual flexibility benefit attributable specifically to the grid tariff [€/year] $C_{\text{original},i}$ = annual total costs before flexibility activation [€/year] $C_{\text{flexible},i}$ = annual total costs after flexibility activation [€/year] $C_{\text{tariff,original},i}$ = annual grid tariff costs before flexibility activation [€/year] $C_{\text{tariff,flexible},i}$ = annual grid tariff costs after flexibility activation [€/year] $C_{\text{tariff},i,m}$ = annual grid tariff costs of profile i under mechanism m [€/year] $E_{\text{import},i,m}$ = annual imported electricity of profile i under mechanism m [kWh/year] $T^{\text{eff}}_{i,m}$ = effective tariff burden of profile i under mechanism m [€/kWh] $T^{\text{eff}}_{i,\text{ref}}$ = effective tariff burden of profile i under the selected reference mechanism [€/kWh]	**Potential flexibility benefits:** €/year. Positive values indicate that activating flexibility reduces consumer costs. **Congestion-reduction potential:** $B_{\text{tariff},i}$ [€/year]. A higher positive tariff-related flexibility benefit indicates a stronger financial incentive for congestion-responsive behaviour. **Incentive of asset ownership:** €/kWh. A negative $\Delta T^{\text{eff}}_{i,m}$ indicates a lower effective tariff burden relative to the selected reference mechanism.
Interaction with electricity price signal	Aligned hours: $S_{\text{aligned}} = \frac{N_{\text{aligned}}}{N} \times 100\%$ Conflicting hours: $S_{\text{conflicting}} = \frac{N_{\text{conflicting}}}{N} \times 100\%$	T_t = grid tariff at hour t [€/kWh] P_t = dynamic electricity price at hour t [€/kWh] N_{aligned} = number of hours in which both price signals provide an incentive in the same direction [hours] $N_{\text{conflicting}}$ = number of hours in which the price signals provide incentives in opposite directions [hours] N = total number of hourly observations [hours] S_{aligned} = share of aligned hours [%] $S_{\text{conflicting}}$ = share of conflicting hours [%]	Share of aligned and conflicting hours [%]. Aligned hours indicate that the grid tariff reinforces the incentive provided by the dynamic electricity price. Conflicting hours indicate that the grid tariff provides an opposing congestion-related incentive.

5.5.4 Defining qualitative criteria metrics

Qualitative criteria cannot be evaluated directly using numerical model outputs. To ensure a consistent and reproducible assessment, each qualitative criterion is translated into a fixed set of observable design characteristics.

These observable characteristics are not introduced independently, but are derived from the same literature and actor-analysis findings from which the qualitative criteria themselves originate. More specifically, the relevant concerns, requirements, and implementation conditions identified in the literature review (Sections 2.3.6–2.3.9) and actor analysis (Sections 4.2.1–4.4) are reviewed for each qualitative criterion. Recurring and concrete conditions that can be observed in the conceptual design of a mechanism are then translated into assessment characteristics. For example, concerns regarding supplier implementation complexity are translated into characteristics such as additional billing logic, metering requirements, and data exchange, while concerns regarding unclear market responsibilities are translated into characteristics related to the allocation of tariff determination, settlement, administration, and flexibility control.

The purpose of this translation is to preserve traceability between the actor and literature findings and the qualitative evaluation. Rather than assigning a score based on an overall impression of a mechanism, the assessment is based on observable characteristics that follow directly from previously identified concerns and requirements.

The assessment characteristics are treated as equally important and are therefore not weighted. For criteria containing five characteristics, the total number of observed requirements is divided into three approximately equal assessment ranges. This simple ordinal classification is selected to maintain transparency and avoid introducing additional subjective weighting. The resulting scores should therefore be interpreted as comparative indicators rather than absolute measures of performance.

For each characteristic, it is assessed whether the mechanism introduces the specified condition or requirement. The resulting observations are subsequently translated into a three-level assessment of *good*, *moderate*, or *poor* using predefined decision rules. The qualitative score therefore follows from explicitly defined characteristics of the mechanism rather than from an overall impression of the evaluator.

The assessment is based on the conceptual specification of each mechanism, including its tariff structure, information requirements, required infrastructure, allocation of responsibilities, and settlement procedure. For transparency, the underlying observations are reported alongside the resulting qualitative assessment.

Simplicity of implementation

The observable characteristics for simplicity of implementation are derived primarily from the implementation concerns identified for suppliers and other market actors in Sections 4.3.2 and 4.4, supplemented by the literature on tariff simplicity discussed in Section 2.3.6. Following from these findings, implementation complexity is assessed using the following five design characteristics:

- Requirement for additional metering or separate asset measurement;
- Requirement for new billing or settlement logic;
- Requirement for an additional registration or subscription system;
- Requirement for new communication or control infrastructure;
- Requirement for additional data exchange between market actors.

Each characteristic is scored as either present (1) or absent (0). The total implementation score therefore ranges from 0 to 5. The qualitative assessment is derived as follows:

- *Good*: 0–1 additional implementation requirements;
- *Moderate*: 2–3 additional implementation requirements;

- *Poor*: 4–5 additional implementation requirements.

Limited additional burdens

Additional burdens are assessed based on recurring tasks or responsibilities introduced by the mechanism after implementation. These assessment characteristics follow from the recurring concerns regarding additional tasks, responsibilities, administration, and coordination identified in the actor analysis, particularly for suppliers, BRPs, CSPs, and aggregators. The following characteristics are considered:

- Recurring manual actions required from consumers;
- Additional recurring billing or settlement activities;
- Recurring administration of subscriptions, contracts, or registered assets;
- Additional forecasting, monitoring, or optimisation responsibilities;
- Additional coordination requirements between market actors.

Each additional recurring burden is scored as present (1) or absent (0). The resulting qualitative assessment is defined as:

- *Good*: 0–1 additional recurring burdens;
- *Moderate*: 2–3 additional recurring burdens;
- *Poor*: 4–5 additional recurring burdens.

Clear purpose of the new system

The operationalisation of clear purpose is based primarily on the consumer-related findings in Section 2.3.8 and Section 4.3.3, which emphasise the importance of understanding why the tariff is applied and how behaviour affects financial outcomes. To capture these aspects, the criterion clear purpose is assessed based on whether the relationship between grid conditions, consumer behaviour, and financial consequences can be directly explained from the tariff design. Three characteristics are evaluated:

- The condition that causes a higher or lower tariff is clearly identifiable;
- The behaviour that allows consumers to reduce their tariff costs is unambiguous;
- The final financial consequence follows directly from the communicated tariff rule without requiring additional ex-post calculations that are unrelated to the consumer's immediate response.

The qualitative assessment is derived as follows:

- *Good*: all three characteristics are satisfied;
- *Moderate*: two characteristics are satisfied;
- *Poor*: zero or one characteristic is satisfied.

Delineation of actor roles

This criterion assesses the extent to which the mechanism requires additional role definition or further delineation of responsibilities between market actors compared with the existing electricity-market structure. A mechanism scores more favourably when it can largely operate within existing and clearly defined actor roles, while mechanisms that introduce new responsibilities, overlapping functions, or additional coordination requirements require more extensive role delineation.

The following characteristics are assessed:

- Additional actor roles need to be introduced;
- Existing actor roles require new responsibilities;
- Responsibilities between actors need to be further delineated;

- Additional coordination arrangements between actors are required;
- New contractual or institutional agreements are required to clarify responsibilities.

Each characteristic is scored as present (1) or absent (0). The qualitative assessment is derived as follows:

- *Good*: 0–1 additional role-allocation requirements;
- *Moderate*: 2–3 additional role-allocation requirements;
- *Poor*: 4–5 additional role-allocation requirements.

Non-discrimination

Non-discrimination is assessed qualitatively by evaluating whether comparable electricity use is treated equally by the tariff mechanism. The assessment focuses on the tariff rule itself rather than on differences in total annual costs between consumer profiles. Differences in costs resulting from different consumption patterns or flexibility choices are therefore not interpreted as discrimination by themselves.

The criterion is based on the principle that comparable electricity behaviour should receive comparable tariff treatment. Within this study, location-dependent tariff treatment is considered a form of discrimination because otherwise comparable consumers may face different charges depending on their connection location. This does not automatically mean that such differentiation is unacceptable. It may be justified where it reflects relevant differences in local network conditions, follows transparent and consistently applied rules, and is proportionate to the congestion-related objective.

The following characteristics are assessed:

- Comparable electricity behaviour receives equal tariff treatment independent of consumer category, asset type, or purpose of electricity use;
- Comparable electricity behaviour is treated independently of the consumer's connection location;
- Any remaining differentiated tariff treatment is based on observable electricity-use or network-relevant behaviour rather than on personal consumer characteristics.

The qualitative assessment is derived as follows:

- Good: all three characteristics are satisfied;
- Moderate: one characteristic is not satisfied or requires additional justification;
- Poor: multiple characteristics are not satisfied.

The assessment therefore distinguishes between the presence of differentiated treatment and its acceptability. The resulting score records the mechanism characteristics regarding the definition of non-discrimination, while Chapter 9 considers whether the differentiation is acceptable in relation to the research objectives and local network conditions.

Table 10: Operationalisation of qualitative evaluation criteria

Criterion	**Observable characteristics**	**Assessment rule**
Simplicity of implementation	Additional metering or asset measurement; new billing or settlement logic; registration or subscription systems; new communication or control infrastructure; additional inter-actor data exchange.	Good: 0–1 requirements. Moderate: 2–3 requirements. Poor: 4–5 requirements.
Limited additional burdens	Recurring consumer actions; additional billing or settlement activities; recurring administration; additional forecasting, monitoring, or optimisation; additional inter-actor coordination.	Good: 0–1 burdens. Moderate: 2–3 burdens. Poor: 4–5 burdens.
Clear purpose of the new system	Clearly identifiable cause of tariff changes; unambiguous desired consumer response; direct relationship between behaviour and financial consequences.	Good: 3 characteristics satisfied. Moderate: 2 satisfied. Poor: 0–1 satisfied.
Delineation of actor roles	Additional actor roles; new responsibilities for existing actors; further delineation of responsibilities; additional coordination arrangements; new contractual or institutional agreements.	Good: 0–1 additional role-allocation requirements. Moderate: 2–3 requirements. Poor: 4–5 requirements.
Non-discrimination	Equal tariff treatment for identical electricity behaviour at the same location and time; no differentiation based solely on consumer or asset type; differentiation only where justified by relevant network conditions.	Good: all characteristics satisfied. Moderate: one characteristic not satisfied or requires justification. Poor: multiple characteristics not satisfied.

Table 10 provides an overview of the qualitative indicators and their assessment rules.

6 Conceptual Design of Grid Tariff Mechanisms

This chapter develops alternative grid-tariff mechanisms for the implementation of dynamic grid tariffs. The design process consists of three steps. First, the design space is defined by identifying the key design variables and their possible configurations. Second, these variables are combined through a morphological analysis to explore alternative mechanism configurations. The morphological analysis is used as an exploration of the design space rather than an exhaustive enumeration of all possible combinations. Finally, a set of conceptually distinct mechanisms is specified and selected for further evaluation.

6.1 Design space

Design variables represent the key system characteristics that can be adjusted in the development of alternative grid-tariff mechanisms. Defining these variables is a crucial step in the design process, as different configurations of their values result in fundamentally different tariff designs.
Based on insights from the literature on dynamic tariff structures and congestion management, as well as findings from the actor analysis and stakeholder interviews, four main design dimensions are identified: *tariff structure*, *exposure limitation*, *time horizon*, and *role and risk allocation*. Together, these dimensions capture the most important degrees of freedom in the design of congestion-related grid tariffs.

Tariff structure
The tariff mechanism determines how tariff levels are formed and how congestion signals are translated into financial incentives for consumers. This dimension is primarily derived from the literature, which distinguishes several pricing approaches, including Real-Time Pricing (RTP), Critical Peak Pricing (CPP), adaptive dynamic tariffs, and capacity-based tariffs.

RTP represents highly dynamic pricing, in which tariff levels closely reflect changing congestion conditions, resulting in strong price signals but also relatively high tariff volatility. CPP introduces dynamic price signals specifically during critical congestion periods, while maintaining more stable tariffs outside these periods. Adaptive dynamic tariffs represent an intermediate approach, in which tariff levels or time blocks are periodically adjusted based on changing network conditions. Capacity subscriptions, by contrast, provide consumers with a predefined capacity level for a fixed periodic fee, resulting in a more stable and predictable cost structure.

Conventional Time-of-Use (ToU) pricing is not included as a separate design option, as its predefined tariff periods do not dynamically respond to changing congestion conditions. Instead, the adaptive dynamic tariff is included to represent tariff structures in which predefined periods or tariff levels can be adjusted in response to network conditions. Together, the selected tariff structures represent different approaches to balancing congestion reflectiveness with tariff stability and predictability.

Exposure limitation
The exposure limitation dimension specifies whether and how the financial consequences of dynamic grid tariffs are modified. This variable follows from the actor analysis, in which tariff volatility and consumer cost exposure were identified as important concerns. Five options are distinguished. No exposure limitation represents full exposure to the dynamic tariff and serves as the benchmark. Flexible demand only limits dynamic exposure to assets that can respond to tariff signals, while excess demand only applies the dynamic tariff to consumption above a predefined subscription threshold. A price cap limits the maximum tariff level that consumers can face. Finally, ex-post redistribution retains the original dynamic tariff during operation but redistributes part of the resulting revenues after the settlement period. This allows the hourly congestion signal to remain unchanged while modifying the final financial consequences for consumers and the DSO.

Time horizon
The time horizon defines how far in advance tariff levels or tariff parameters are determined and communicated to consumers and market parties. This dimension is informed by both literature and

interview insights, and ranges from highly dynamic to highly stable configurations.
At one extreme, real-time determination provides little or no advance knowledge of tariff levels, maximising responsiveness to actual network conditions but limiting predictability. However, consumers and market parties pointed out that in the case of hourly dynamic grid tariffs, they require at least day-ahead determination and communication. Therefore, real-time is only selected as time horizon in the extreme benchmark design.
Intermediate options, such as *day-ahead* pricing, provide some level of predictability while maintaining responsiveness to expected system conditions. At the other extreme, *monthly or yearly* tariff structures offer high predictability and simplicity, but significantly reduce the responsiveness of the tariff to short-term congestion.
The choice of time horizon therefore directly affects both the effectiveness of price signals and their usability for consumers, representing a trade-off between dynamic efficiency and predictability.

Role and risk allocation
The role and risk allocation dimension specifies how responsibilities for the implementation and administration of the tariff mechanism are distributed among market actors. While the DSO determines the underlying congestion signal, different actors may be responsible for translating this signal into tariffs, administering subscriptions, billing consumers, or managing the resulting price risk.

In a direct configuration, consumers are exposed to the grid tariff without an intermediary taking responsibility for the associated price risk. Alternatively, existing market actors such as suppliers, CSPs, or aggregators may take on an intermediary role. This becomes particularly relevant for mechanisms involving capacity subscriptions or dynamic price exposure, where an intermediary may administer the subscription or absorb part of the short-term tariff risk on behalf of consumers.

Role delineation therefore determines not only the operational responsibilities within the mechanism, but also how dynamic tariff exposure and associated risks are distributed between actors. This creates a trade-off between direct price reflectiveness and consumer protection on the one hand, and additional coordination and implementation complexity on the other.

Conclusion
Together, these four design variables define the main degrees of freedom within the design space and form the foundation for the morphological analysis and subsequent mechanism construction. Table 11 provides an overview of the identified design variables and their respective options.

Table 11: Design variables and corresponding options for the morphological analysis

Design variable	**Options**
Tariff structure	Real-Time Pricing (RTP); Critical Peak Pricing (CPP); Adaptive Dynamic Tariffs (ADT); Capacity Subscription
Exposure limitation	No exposure limitation; Flexible demand only; Excess demand only; Price cap; Ex-post redistribution
Time horizon	Real-time; Day-ahead; Monthly; Yearly
Role and risk allocation	Direct consumer exposure; Supplier intermediation; CSP/aggregator intermediation; DSO intermediation

6.2 Morphological analysis and design construction

Following the definition of the design variables and their corresponding options, a morphological analysis is applied to systematically explore the design space. This method consists of defining key dimensions of the design space and identifying possible options for each dimension (Ritchey, 1998). The objective of this step is not to exhaustively evaluate all possible combinations, but to identify a representative set of configurations that capture the key trade-offs in the system.

6.2.1 Identification of extreme configurations

First, extreme configurations are constructed based on the identified trade-offs. These extreme cases represent the boundaries of the design space and serve as analytical reference points. For example, a

fully dynamic real-time pricing (RTP) mechanism applied to all load with user-based risk allocation represents maximum exposure and reflectivity, while capacity-based mechanisms with DSO risk allocation represent maximum predictability and protection. Allocating the risk to the DSO implies that the DSO provides risk-hedging arrangements to limit consumers' exposure to tariff risk. In return, the DSO bears the risk that tariff revenues may be insufficient to recover its required network costs.

These extreme configurations are not necessarily intended as realistic solutions, but rather to highlight the fundamental tensions between design objectives such as price signal strength, complexity, and risk exposure. An overview of the constructed extreme configurations is shown in table 12.

Table 12: Exploration of extreme configurations within the design space

Extreme	**Tariff structure**	**Exposure limitation**	**Time horizon**	**Role / risk allocation**
Maximum congestion reflectiveness	RTP	None	Real-time	–
Maximum volatility	RTP	None	Real-time	–
Maximum exposure	RTP	None	Real-time	Direct consumer
Maximum predictability	Capacity subscription	No dynamic exposure	Yearly	DSO intermediation
Maximum risk protection	Capacity subscription	No dynamic exposure	Long-term	CSP/Aggregator

Table 12 shows that several extreme objectives result in similar configurations of the design variables. Maximum reflectivity, volatility and consumer exposure converge towards a configuration based on RTP, without exposure limitation and with direct consumer exposure. This configuration provides the strongest possible relationship between network conditions and consumer tariffs, but simultaneously exposes consumers to the largest degree of tariff variation and financial risk.
At the opposite boundary, maximum predictability and risk protection converge towards a capacity subscription with no direct exposure to short-term dynamic tariffs. Consumers instead face a predefined capacity level and a stable periodic charge. This configuration provides a high degree of cost predictability and protection against short-term tariff volatility, but weakens the direct relationship between short-term congestion conditions and consumer costs.

These configurations therefore represent two opposing boundaries of the design space: a maximum-reflectivity configuration and a maximum-stability configuration. The remaining mechanism alternatives are constructed between these boundaries by selectively modifying the exposure limitation and role allocation dimensions, thereby retaining part of the dynamic congestion incentive while mitigating its associated risks.

6.2.2 Construction of intermediate configurations

The extreme configurations illustrate the central trade-off between congestion reflectiveness and consumer protection. At one boundary, unrestricted RTP provides a highly congestion-reflective signal, but also results in relatively high tariff volatility and direct financial exposure. At the other boundary, a stable subscription-based structure provides greater predictability and protection, but responds less directly to short-term changes in congestion conditions. Neither boundary necessarily provides a desirable grid-tariff mechanism. Intermediate configurations are therefore constructed by modifying individual design variables or combining elements from both boundaries.

Full EmPower is retained as the benchmark configuration representing the high-reflectiveness boundary. Starting from this benchmark, several design directions are explored to reduce different sources of risk while retaining congestion-related incentives.

Design direction 1

A first design direction is to limit *which demand is exposed* to the dynamic tariff. Rather than applying RTP to all household electricity use, dynamic exposure can be restricted to flexible assets such as electric vehicles, heat pumps, batteries, and PV systems. This concentrates the congestion-related

incentive on demand with a greater ability to respond while protecting other household consumption from dynamic tariff exposure. This design direction results in the *Targeted RTP* configuration.

Design direction 2

A second design direction is to limit *how much demand is exposed* by combining a subscription-based structure with dynamic RTP. Consumers pay a stable periodic fee for a predefined level of electricity use, while consumption exceeding this level remains exposed to the dynamic congestion tariff. This combines a relatively predictable base component with a congestion-reflective marginal price signal. Such a structure also requires a market actor to administer the subscription, communicate the applicable conditions, and potentially manage part of the associated tariff risk on behalf of consumers.
Two variants are considered. In the *Flex Volumetric* configuration, the subscription threshold is defined as a predefined electricity volume in kWh. Consumption beyond this volume is exposed to RTP. In the *Flex Capacity* configuration, the subscription threshold is instead defined as a capacity level in kW, with demand above this capacity exposed to RTP during congestion periods. The capacity-based variant therefore links dynamic exposure more directly to peak power demand, while both configurations provide greater stability than unrestricted RTP.

Design direction 3

A third design direction retains the dynamic RTP structure during operation, while modifying both the tariff level and the final financial settlement. The tariff level can be adjusted to support sufficient cost recovery for the DSO, while an ex-post redistribution mechanism applies a financial correction after the settlement period. Consumers therefore continue to face a congestion-reflective RTP signal when making consumption decisions, while the resulting tariff revenues can subsequently be redistributed. This separates the behavioural incentive from the final financial settlement and results in the *Ex-post Bonus* configuration.

Design direction 4

A fourth design direction modifies the *time horizon and temporal variability* of the tariff itself. Instead of responding to congestion conditions on an hourly basis, tariff periods can be determined for a longer period based on expected or observed congestion patterns. Periodically updating these peak and off-peak periods retains a relationship with local network conditions while reducing short-term tariff fluctuations and increasing predictability. This results in the *Adaptive Dynamic Tariff (ADT)*, which occupies an intermediate position between predefined static tariff periods and fully dynamic RTP.

Design direction 5

Finally, the *role and risk allocation* dimension affects several of the intermediate configurations. In subscription-based mechanisms, an actor such as a supplier or aggregator may be responsible for administering subscriptions, advising consumers on suitable subscription levels, and managing part of the financial risk associated with dynamic exposure. Role allocation can also be used more directly as a congestion-management instrument. Instead of relying solely on consumers to respond to dynamic price signals, a coordinating actor can obtain contractual access to flexible assets and activate this flexibility when congestion occurs. This shifts part of the responsibility for congestion response from individual consumers towards an aggregator or other coordinating market actor and results in the *Capacity Steering Contract (CSC)*. Such contracts can provide suppliers or aggregators with a direct means to incentivise and coordinate flexibility, while offering participating consumers financial compensation for making their flexible capacity available.

The resulting configurations therefore mitigate the risks of unrestricted RTP through different design choices: limiting the type of demand exposed, limiting the quantity of demand exposed, modifying the final financial settlement, reducing the temporal variability of the tariff, or reallocating responsibility for flexibility activation. Together with Full EmPower as the benchmark configuration, these approaches form the basis for the representative mechanism set selected in the following section.

6.2.3 Resulting set of representative designs

Based on the exploration of the design space, seven representative grid-tariff mechanisms are selected for further development. The purpose of this selection is not to cover every possible combination of design variables, but to include conceptually distinct configurations that represent different approaches to balancing congestion reflectiveness, predictability, and consumer protection.

Full EmPower is retained as the benchmark and represents the high-reflectiveness boundary. Consumers are directly exposed to congestion-based RTP, subject only to the predefined price cap of the EmPower tariff. The remaining designs modify different elements of this benchmark. *Targeted EmPower* limits exposure to flexible assets, while *Flex Volumetric* and *Flex Capacity* combine a stable subscription component with dynamic pricing above a predefined threshold. The *Ex-post Bonus* retains the dynamic price signal while modifying the final financial settlement, and the *Adaptive Dynamic Tariff (ADT)* increases predictability by reducing short-term tariff variability. Finally, the *Capacity Steering Contract (CSC)* shifts part of the congestion response from price-based consumer behaviour towards contractual coordination of flexible assets.

Table 13 summarises the resulting mechanism set and the main design principle represented by each configuration. Together, these mechanisms cover the main design directions identified in the morphological analysis and form the basis for the detailed conceptual designs presented in Section 6.3.

Table 13: Resulting set of representative grid-tariff system designs

Mechanism	**Main design direction**	**Conceptual principle**
Full RTP	Maximum reflectivity	All consumption is directly exposed to congestion-based RTP without exposure limitation.
Targeted RTP	Demand-based protection	RTP is applied only to registered flexible or congestion-relevant assets, limiting exposure of other household demand.
Ex-post Bonus	Ex-post financial redistribution	The original hourly RTP signal is retained, while tariff revenues are redistributed after the settlement period through an ex-post correction.
Flex Volumetric	Volume-based protection	A predefined consumption volume is covered by a subscription, while excess consumption is exposed to RTP.
Flex Capacity	Capacity-based protection	A predefined capacity level is covered by a subscription, while demand exceeding the subscribed capacity is exposed to RTP.
Adaptive Dynamic Tariff (ADT)	Temporal stability	Tariff periods are periodically adjusted based on local congestion patterns, providing greater stability than RTP.
Capacity Steering Contract (CSC)	Direct flexibility control	Registered flexible assets can be controlled during congestion periods based on a contractual arrangement rather than relying solely on dynamic price exposure.

6.3 Conceptual tariff mechanism design

The morphological analysis resulted in seven representative mechanism designs that occupy different positions within the identified design space. This section further specifies how each mechanism operates and how the selected design directions are translated into concrete tariff arrangements. For each mechanism, the tariff structure, exposure limitation, time horizon, and role allocation are specified, followed by a description of the resulting financial incentive and the main expected trade-offs.

The mechanisms are presented from the configuration with the highest direct exposure to dynamic

congestion signals towards configurations that increasingly limit, restructure, or replace this exposure. Full EmPower serves as the reference configuration. The remaining mechanisms modify specific elements of this benchmark through targeted exposure, financial protection, subscription-based protection, increased temporal stability, or direct coordination of flexibility.

6.3.1 Full EmPower

Full EmPower represents the benchmark configuration with the highest direct exposure to dynamic congestion signals. Consumers pay a grid tariff for each kWh of electricity consumed, with the tariff level varying according to the congestion intensity during that hour. As a result, consumption during periods of severe congestion is more expensive, while consumption outside congestion periods faces a lower or zero congestion tariff. This creates a direct financial incentive to shift electricity consumption away from congested periods.

The mechanism uses RTP as its tariff structure and does not apply any exposure limitation: all household electricity consumption is subject to the congestion-based tariff. Tariffs vary at an hourly resolution. However, the tariff values should be communicated at least day-ahead to allow consumers and automated energy management systems to respond. Interview findings indicated that a longer announcement horizon, for example one week ahead, may be preferred by market actors because household consumption and flexibility often follow weekly patterns.
The DSO determines the congestion signal and corresponding grid tariff based on local network conditions. Tariff information is subsequently communicated to the consumer and relevant market actors, while billing can be performed through the existing billing relationship between the consumer and supplier or DSO. The consumer ultimately bears the financial risk associated with variations in the dynamic tariff.

Grid tariffs are constructed as a function of congestion intensity. Higher congestion levels result in higher tariffs, while low or negative congestion (e.g., during PV injection periods) leads to lower or even negative tariffs. This creates a dynamic price signal that reflects real-time grid conditions.

The tariff formulation is based on the following variables:

- **C-max**: The effective transformer-capacity parameter used for tariff generation in the simulated congestion scenario, measured in kW. The physical transformer capacity is 800 kW, while an effective value of 400 kW is used in the simulation to construct the congestion scenario evaluated in this research.
- **thres**: The safety threshold of the transformer, expressed as a share of the maximum capacity under which the transformer can operate safely.
- **C-safe**: The safe operating capacity of the transformer, measured in kW, defined as $C_{safe} = C_{max} \cdot thres$.
- **Con-tot**: The total hourly congestion, measured in kW. This value reflects congestion intensity and is calculated by subtracting the safe capacity from the actual load, in cases where the load exceeds C_{safe}.
- **Tariff-static**: The static component of the tariff, representing the base tariff level during periods without congestion (€/kWh).
- **Tariff-dynamic**: The dynamic component of the tariff (€/kWh), which is added to the static tariff based on congestion intensity.

The resulting tariff level is calculated as:

$$\frac{\max\left(\min(\text{Con-tot}(t),\, C_{\max} - C_{safe}),\, C_{safe} - C_{\max}\right)}{C_{\max} - C_{safe}} \cdot \text{Tariff}_{dynamic} + \text{Tariff}_{static}.$$

The use of the `max` and `min` functions ensures that congestion levels are bounded within the available congestion space, defined as the range between the maximum transformer capacity and the safe

capacity.
The `min` function caps positive congestion levels, representing consumption-related congestion when demand exceeds the safe capacity. Conversely, the `max` function caps negative congestion, which corresponds to injection congestion, typically occurring during periods of high photovoltaic generation. The resulting congestion value is normalised by the size of the congestion space, yielding a relative congestion factor between -1 and 1. This factor is then multiplied by the dynamic tariff component and added to the static tariff, resulting in the final tariff level.

This configuration prioritises tariff reflectiveness and congestion-responsive incentives. Its main advantage is the strong relationship between local network conditions and the costs experienced by consumers. At the same time, this results in relatively high tariff volatility and consumer cost exposure. Full EmPower therefore serves as the reference configuration against which the risk-mitigating mechanisms are compared.

6.3.2 Targeted EmPower

Targeted EmPower retains the congestion-based RTP structure of the benchmark mechanism but limits its application to registered flexible assets. Dynamic grid tariffs are therefore applied to electricity consumed or produced by assets such as electric vehicles, heat pumps, batteries, and PV systems, while remaining household consumption is excluded from the dynamic tariff. The tariff applied to these assets continues to vary according to congestion intensity during each hour.

This exposure limitation specifically targets loads that have a greater technical ability to respond to congestion signals. The design direction originates from interview findings in which concerns were raised about exposing consumers with limited flexibility to highly dynamic grid tariffs. By concentrating the dynamic incentive on large flexible assets, the mechanism aims to retain a substantial share of the available flexibility while reducing unnecessary tariff exposure for inflexible household demand.
Implementation requires flexible assets to be identified and registered and their electricity use to be measured separately. Suppliers or another coordinating market actor could administer this registration and process the required measurement data, while the DSO remains responsible for determining the congestion signal and corresponding RTP tariff. As with Full EmPower, hourly tariff values should be communicated sufficiently in advance to enable automated response.

Compared with Full EmPower, the mechanism reduces consumer cost exposure and concentrates incentives on demand with a greater ability to respond. This protection comes at the expense of reduced overall tariff coverage and additional implementation requirements related to asset registration, measurement, and automation.

6.3.3 Ex-post Bonus

The Ex-post Bonus mechanism retains the hourly congestion-based EmPower tariff during operation, but introduces an additional settlement step after the evaluation period. Consumers are therefore initially exposed to the same dynamic congestion signal as under Full EmPower. After the resulting tariff revenues have been determined, an ex-post financial correction is calculated and redistributed to consumers.

The purpose of the mechanism is to separate the behavioural price signal from the final financial settlement. During consumption, consumers continue to face the original congestion-related tariff and therefore retain an incentive to shift flexible demand away from high-tariff periods. The ex-post correction does not alter these hourly tariff levels retrospectively for behavioural decision-making, but instead modifies the final annual tariff payment.

In the configuration evaluated in this research, the ex-post correction is calibrated such that the aggregate tariff revenue of the DSO is restored to the revenue obtained under the static reference tariff. The required correction is determined after calculating the gross tariff revenues generated by the dynamic tariff. The resulting difference between dynamic tariff revenue and the reference revenue is subsequently redistributed across consumers as an ex-post bonus or correction.
The DSO remains responsible for determining the underlying congestion-based tariff and the required revenue level. The calculation and distribution of the ex-post correction introduces an additional

settlement responsibility, which could be administered by the DSO, supplier, or another designated market actor. This therefore increases administrative complexity compared with Full EmPower.

The main advantage of the Ex-post Bonus is that it preserves the hourly congestion-reflective signal and associated flexibility incentives while enabling aggregate cost recovery to be corrected afterwards. However, it does not directly reduce the volatility of the tariff signal faced during operation, and aggregate revenue neutrality does not guarantee that individual consumers are financially protected. Depending on their consumption profile, some consumers may still face higher annual costs than under the static tariff. The mechanism therefore represents a trade-off between maintaining the original dynamic incentive, restoring DSO revenue recovery, and limiting individual consumer cost exposure.

6.3.4 Flex Volumetric

Flex Volumetric combines a volumetric subscription with congestion-based RTP. Consumers select a predefined monthly electricity volume for a fixed subscription fee. As long as cumulative consumption remains within the subscribed volume, consumption is covered by the subscription. Once the subscribed volume is exceeded, additional consumption during the remainder of the subscription period is exposed to the congestion-based RTP tariff.

The subscribed volume therefore provides a predictable baseline and limits the amount of consumption exposed to dynamic tariff risk. Different subscription levels allow households to select a combination of fixed costs and dynamic exposure that corresponds to their expected consumption and willingness to accept risk. A lower subscription can reduce the fixed subscription fee but increases the probability of exposure to RTP, whereas a higher subscription provides greater cost protection at a higher fixed cost. Selecting an appropriate subscription requires information about expected household consumption and flexibility. Because it may be unrealistic to expect every household to continuously make an economically optimal subscription choice, an aggregator can support consumers by forecasting consumption and advising on the appropriate subscription level. The aggregator's role can therefore extend beyond administration towards optimisation of the subscription for participating households. The DSO remains responsible for determining the underlying congestion-based RTP signal.

For the quantitative evaluation, three volumetric subscription levels are defined: 200, 450, and 650 kWh per month. These levels were derived from the monthly electricity-import characteristics of the eight consumer profiles. The 75th percentile of monthly import was used as the main reference point, resulting in three broad groups of low-, medium-, and high-volume consumers. The purpose of this calibration is to cover a substantial share of normal monthly consumption while retaining exposure to the dynamic tariff during relatively high-consumption months. The corresponding monthly fees are €25, €34, and €40. These fees were calibrated separately by considering both consumer cost exposure and population-weighted DSO tariff revenues. The detailed calibration procedure and profile assignments are provided in Appendix E.

The mechanism increases predictability compared with Full EmPower while preserving a dynamic incentive once the subscribed volume is exceeded. Its main limitation from a congestion-management perspective is that monthly electricity volume is only indirectly related to network congestion. A household can remain within its monthly subscription while still creating a high coincident peak during congested hours. This motivates the alternative capacity-based subscription mechanism.

6.3.5 Flex Capacity

Flex Capacity replaces the volumetric subscription with a subscribed capacity level. Consumers select a predefined capacity in kW and pay a corresponding fixed subscription fee. Lower subscribed capacity results in lower fixed costs, while consumption exceeding the subscribed capacity is exposed to the congestion-based RTP tariff. The dynamic component consists of the same RTP signal as the EmPower model, ensuring that capacity exceedance is financially relevant specifically when additional network loading contributes to congestion.

The mechanism therefore combines predictable subscription costs with a dynamic marginal incentive. Consumers can reduce their expected costs either by selecting an appropriate subscription level or

by using flexibility to remain below their subscribed capacity during congestion periods. As with the volumetric mechanism, an aggregator can support households in selecting and periodically adjusting the subscription based on historical demand and available flexibility.

For the quantitative evaluation, three capacity subscription levels are defined: 1, 3, and 6 kW. These levels were derived from the hourly import characteristics of the consumer profiles. Different capacity thresholds were evaluated based on both the number of exceedance hours and the share of imported electricity occurring above the subscribed capacity. The objective was to cover normal household demand while maintaining dynamic exposure to relatively high, often asset-driven, capacity peaks. This ensures that the subscription provides financial protection without removing the incentive to reduce high demand during congestion periods. The corresponding monthly fees are €26, €30, and €40 and were calibrated by considering consumer cost exposure and population-weighted DSO tariff revenues. The detailed calibration procedure and profile assignments are provided in Appendix E.

The capacity-based design has a stronger physical relationship with congestion than the volumetric subscription. Network congestion is primarily driven by coincident power demand relative to available network capacity rather than by total monthly electricity consumption. Consequently, applying the subscription threshold in kW provides a more congestion-reflective basis for determining when dynamic exposure occurs.

Compared with Full EmPower, the mechanism provides a predictable base component and limits dynamic exposure to capacity exceedance during relevant periods. Compared with the volumetric subscription, it is more directly related to the physical cause of network congestion. However, it also introduces additional complexity through capacity selection and may create financial consequences for households with high unavoidable peak demand.

6.3.6 Adaptive Dynamic Tariff

The Adaptive Dynamic Tariff (ADT) provides a more predictable alternative to hourly RTP by periodically adapting predefined tariff periods to observed or expected local congestion patterns. The mechanism can be interpreted as an adaptive form of Time-of-Use pricing: instead of using permanently fixed peak and off-peak periods, the DSO periodically updates these periods based on changing network conditions, for example at transformer level.
In the conceptual design considered here, tariff periods are updated on a monthly basis.

Construction of ADT tariff blocks

The ADT schedule is constructed separately for each month. First, congestion intensity is averaged across all observations of the same hour of the day within that month, producing 24 mean hourly values. These values are classified using quantile thresholds into three possible tariff categories: Off-peak, Normal, and Peak. Hours assigned to the same category do not necessarily form a continuous interval. For each month and category, the tariff is calculated as the mean of the expected hourly EmPower tariffs assigned to that category. The resulting daily schedule is repeated throughout the month.

Not every month contains all three categories. When congestion is limited and the mean hourly congestion values show little variation or contain many identical values, the quantile-based classification may produce fewer populated categories. In the simulated year, July, September, and October each contain a single category, resulting in a constant tariff throughout the month. Although these hours are labelled Peak in the model output, their tariff levels remain close to the base tariff; the label does not indicate continuously high congestion. Table 36 in Appendix D reports the populated categories, tariff levels, and corresponding numbers of hours for each month.

Because the tariff blocks are fixed for one month each, consumers know in advance which periods will face higher or lower grid tariffs during the following month. No additional exposure limitation is applied, as the reduction in short-term tariff variability itself provides a degree of protection and predictability. The DSO is responsible for identifying local congestion patterns and determining the corresponding tariff periods.

ADT sacrifices part of the short-term reflectiveness of RTP in exchange for greater stability and predictability. Actual congestion may differ from the patterns on which the tariff periods were based, meaning that the tariff does not always correspond directly to real-time network conditions. However, the longer announcement horizon makes the tariff easier for consumers and market parties to anticipate and incorporate into their consumption planning.

6.3.7 Capacity Steering Contract

The Capacity Steering Contract (CSC) differs from the preceding mechanisms by introducing direct coordination of flexible assets. Consumers voluntarily register eligible flexible assets and receive financial compensation in exchange for granting a coordinating actor the authority to temporarily reduce or shift their electricity demand during periods of network congestion. The mechanism therefore replaces part of the reliance on consumer response to price signals with contracted access to flexibility. Although CSC and the capacity subscription mechanism are both capacity-oriented, they rely on different underlying principles. Flex Capacity uses a tariff-based incentive for consumers to remain within a subscribed capacity, whereas a Capacity Steering Contract establishes a contractual commitment to make predefined flexibility or capacity available during congestion periods.

During congestion periods, registered assets can be controlled within predefined contractual conditions. These conditions specify which assets may be controlled and under which circumstances intervention is permitted. Outside these interventions, consumers retain normal control over their assets. Financial compensation provides the incentive for consumers to participate and compensates for the temporary loss of control or flexibility.
In the proposed configuration, the CSC is combined with an Adaptive Dynamic Tariff for the remaining household demand. The ADT provides a relatively stable incentive for general peak-shaving behaviour, while the steering contract gives the coordinating actor access to specific flexible assets when stronger congestion management is required. The DSO determines when congestion intervention is required, while an aggregator or supplier can coordinate the participating assets and manage the contractual relationship with households.

The main advantage of this design is greater certainty that contracted flexibility can actually be activated during critical congestion periods. It also protects general household consumption from highly volatile RTP exposure. The trade-off is increased organisational and technical complexity, including asset registration, communication infrastructure, contractual arrangements, and consumer acceptance of external control over flexible assets.

6.4 Scope of the quantitative evaluation

The conceptual design phase resulted in seven representative grid-tariff mechanisms. All seven mechanisms are retained as relevant design alternatives, but not all can be evaluated within the same quantitative modelling framework. The quantitative evaluation is therefore limited to mechanisms that can be represented consistently using the market-based simulation model developed in this research.

Three conditions are used to determine whether a mechanism is suitable for quantitative evaluation. First, the mechanism must translate grid conditions into a tariff or financial exposure rule that can be applied to the household demand profiles. Second, consumer response must be representable through the flexibility assumptions included in the model. Third, the mechanism must be evaluable without introducing additional behavioural, contractual, or control assumptions that are not required for the other designs. Applying these conditions results in six mechanisms being selected for quantitative evaluation.

First, the current Dutch tariff mechanism is modelled, which consists of a static yearly fee. Next, Full EmPower (EmPower) is retained as the benchmark, representing unrestricted exposure to congestion-based dynamic pricing. Targeted EmPower is included to evaluate the effect of limiting dynamic tariff exposure to flexible assets. The Ex-post Bonus is included to investigate whether financial consequences can be redistributed after settlement while retaining the original hourly congestion signal. Flex Volumetric and Flex Capacity are included to compare two forms of subscription-based exposure limitation, while the Adaptive Dynamic Tariff is included to assess the effect of reducing the temporal

variability of the tariff signal. Together, these six mechanisms can be represented within the same simulation framework by modifying the tariff structure, exposure limitation, or settlement rule while keeping the underlying consumer and network inputs consistent.

The Capacity Steering Contract (CSC) is not included in the quantitative simulation. Although the mechanism could in principle be modelled, its additional analytical value within the current set of quantitative designs is limited. Capacity-oriented congestion reduction is already represented through the Flex Capacity mechanism, while the flexibility potential of household assets is captured through the optimisation of flexible demand. The CSC differs from these mechanisms mainly through its contractual form, in which flexibility is made available to a coordinating actor in exchange for compensation rather than being activated solely in response to a tariff signal.

Quantitatively evaluating this distinguishing feature would require additional assumptions regarding, among others, the level and structure of compensation, participation conditions, activation rules, and contractual availability of flexibility. These parameters cannot be derived sufficiently reliably from the available data and would therefore have to be chosen largely on the basis of assumptions. As a result, the quantitative outcomes would be strongly dependent on the specific contract design rather than on the general mechanism principle itself. For this reason, CSC is retained as a conceptually relevant alternative, but is excluded from the formal comparative evaluation. Its distinguishing contractual and organisational characteristics are discussed conceptually, as evaluating them consistently would require additional assumptions that are not supported by the available data. The exclusion of CSC should therefore be interpreted as an evaluation-scope decision rather than as an indication that the mechanism is technically infeasible or irrelevant.

An overview of the selected mechanisms is provided in table 14.
The mechanisms are referred to as Full EmPower, Targeted EmPower, Flex Volumetric, Flex Capacity, Ex-post Bonus, and ADT. Flex Volumetric and Flex Capacity are also referred to as EmPower Flex Volumetric and EmPower Flex Capacity, respectively. In figures and compact tables, the abbreviated labels Full RTP, Targeted, Flex Vol., Flex Cap., Ex-post, and ADT are used.

Table 14: Selection of mechanisms for evaluation

Mechanism	**Reason for inclusion**
Full EmPower	Benchmark representing unrestricted congestion-based dynamic pricing.
Targeted EmPower	Tests the effect of limiting dynamic tariff exposure to flexible assets.
Ex-post Bonus	Tests whether aggregate tariff revenues can be redistributed ex post while retaining the original hourly congestion signal and flexibility incentives.
Flex Volumetric	Tests volume-based protection and enables comparison with capacity-based incentives.
Flex Capacity	Tests capacity-based protection and its direct incentive for peak shaving.
Adaptive Dynamic Tariff (ADT)	Tests increased predictability through reduced temporal tariff variability.

7 Model setup

In the next chapter, the defined designs from chapter 6 will be evaluated against the performance criteria selected in chapter 5. To assess performance on the quantitative criteria, a market-based simulation model was developed to generate the numerical outputs required for the evaluation.

7.1 Motivation

A simulation model is developed to generate the numerical outputs required for the quantitative evaluation defined in Chapter 5. In this research, quantitative evaluation refers to the calculation and comparison of predefined numerical performance indicators across the selected grid-tariff mechanisms. The model therefore functions as an analytical tool that produces the tariff, consumer-cost, revenue, flexibility, and signal-interaction outputs from which these indicators are calculated.

As discussed in the literature review (Section 2.3.4), different modelling approaches can be used to evaluate dynamic tariff mechanisms depending on the objective of the analysis. Power-flow models primarily focus on physical network behaviour, such as voltage levels and power flows (Balamurugan & Srinivasan, 2011; Jha et al., 2023), whereas market-based simulation and optimisation approaches can be used to evaluate how tariff signals affect consumer behaviour and financial outcomes.

Since this research focuses on the consumer-level and system-level consequences of alternative grid-tariff system designs, rather than on detailed physical electricity flows, a market-based simulation approach is adopted. Network loading and congestion conditions are therefore used as exogenous inputs to the model. The model then determines how each mechanism translates these conditions into tariff signals and how these signals affect household costs, tariff revenues, flexibility incentives, and interactions with other market signals.

Using the same network conditions, household profiles, and simulation period for each mechanism enables a controlled comparison of their quantitative performance. The resulting outputs are subsequently evaluated using the indicators operationalised in Chapter 5.

7.2 Model objective

The main objective of the model is to provide quantitative insight into the performance of the selected tariff mechanism designs, considering both system-level and consumer-level effects. The model simulates how the different designs translate network conditions into grid tariffs and how these tariffs affect consumers with different demand profiles and levels of flexibility.
The model provides the numerical outputs required to calculate the quantitative indicators defined in Chapter 5. These include cost recovery, consumer cost exposure, tariff volatility, tariff reflectiveness, economic incentives for flexibility, and interaction with electricity price signals. Qualitative criteria, including non-discrimination, simplicity of implementation, additional burdens, clear purpose, and delineation of actor roles, are evaluated separately based on the conceptual characteristics of each mechanism.

7.3 Model structure

The model is structured as a tariff simulation model that represents electricity consumption and generation, grid congestion conditions, tariff formation, consumer flexibility, and the resulting financial outcomes over a defined time horizon. Rather than simulating electricity-market clearing or interactions between supply and demand, the model focuses on how alternative grid tariff mechanisms translate predefined grid conditions into financial incentives and how flexible consumers can respond to these signals. A conceptual overview of the structure of the model is shown in figure 2. Below this graph, the key steps will be explained.

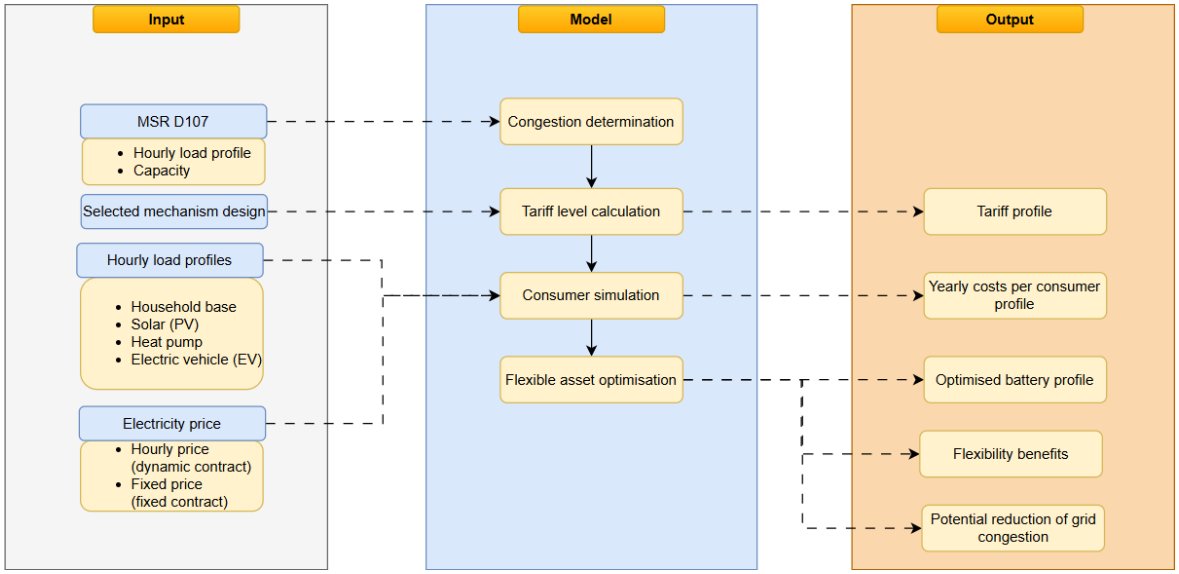

Figure 2: Conceptual diagram: model structure

1. **Network and congestion input**
   The network loading profile of medium-voltage substation MSR D107 forms the basis for determining network congestion. The dataset contains the hourly loading of the substation over the simulation period. Together with the available network capacity, this profile is used to determine whether and to what extent the network is congested at each time step. The resulting congestion signal forms the network input for the tariff calculation.

2. **Tariff generation**
   The congestion signal is translated into a grid tariff according to the selected tariff structure. In general, the tariff level reflects the utilisation of the network: increasing congestion results in a stronger price signal intended to discourage electricity use during constrained periods. Depending on the mechanism, this signal can also apply differently to consumption, injection, flexible demand, or capacity exceedance.

   The exact relationship between congestion and the tariff differs between the selected mechanism designs. Therefore, the tariff formulation and mechanism-specific parameters were specified separately for each design in Chapter 6. This allows all designs to be evaluated using the same network and consumer inputs while varying the way in which consumers are exposed to congestion-related grid tariffs.

3. **Consumer profiles**
   To evaluate how the selected grid-tariff mechanisms affect different types of consumers, eight consumer archetypes are included in the model. As discussed in the literature review (Chapter 2), the impact of dynamic tariffs depends strongly on household characteristics and the availability of flexible energy assets. The archetypes therefore differ according to the presence of photovoltaic (PV) generation, an electric vehicle (EV), a heat pump, and battery storage.

   Hourly profiles are constructed for the household base demand and each of these assets. By combining these profiles, annual electricity profiles are obtained for each consumer archetype. The resulting archetypes range from a household without flexible assets to a highly flexible prosumer with multiple energy technologies. This allows the same tariff mechanism to be applied to consumers with different consumption, generation, and flexibility characteristics.

   Table 15 provides an overview of the consumer archetypes included in the model.

Table 15: Overview of consumer archetypes and their characteristics

Consumer archetype	Description
Basic household	Baseline household electricity demand
PV household	Household demand combined with PV generation
EV household	Household demand with EV charging
Heat-pump household	Household demand with heat-pump demand
Heat-pump + EV household	Combination of heat-pump demand and EV charging
EV + PV household	Combination of PV generation and EV charging
Heat-pump + EV + PV household	Combination of heat-pump demand, EV charging and PV generation
Smart prosumer (EV + PV + battery + heat pump)	Combination of generation and multiple flexible assets

4. **Consumer simulation**
   For each consumer archetype, the hourly electricity profile is combined with the generated grid tariff and the applicable electricity price. The model distinguishes between a dynamic electricity contract, for which the electricity price varies hourly, and a fixed electricity contract.
   At each time step, the model determines the resulting electricity import or export and calculates the associated electricity and grid tariff costs. Repeating this calculation over the full simulation period results in the annual electricity costs for each consumer archetype under each grid-tariff system design. This enables the financial exposure of different types of consumers to be compared consistently.

5. **Flexible asset optimisation**
   Flexible assets are modelled by allowing part of their electricity demand or generation to respond to the combined grid tariff and electricity price signal. The feasible response depends on the technical characteristics of the asset. EV charging and heat-pump demand can be shifted within predefined flexibility constraints. For EV charging, 40% of daily electricity demand can be shifted to hours with lower combined electricity prices and grid tariffs (Li et al., 2025). For heat pumps, this share is 40% during December, January, and February and 60% during the remaining months (Haupt, Male, Mohapatra, & Hamacher, 2026). Demand is shifted within the same day, subject to the power limits of each asset. PV generation can be curtailed when exporting surplus electricity is economically unfavourable.
   Battery storage is modelled using a cost-minimisation optimisation approach. As discussed in the literature review (Chapter 2), household-level optimisation with time-dependent electricity prices is suitable for representing the response of battery storage to dynamic price signals (Selim, Mo, Pota, & Dong, 2023). The battery therefore charges and discharges in response to the combined electricity price and grid tariff while remaining subject to technical constraints, including storage capacity, charging and discharging power limits, and efficiency losses.

   The resulting optimised battery profile represents the economically optimal response from the perspective of the consumer. Comparing this profile with the situation without battery optimisation also provides insight into the extent to which consumer flexibility can respond to congestion-related tariff signals.

6. **Model outputs and cost calculation**
   The model produces a set of outputs for each grid-tariff system design and consumer archetype. The generated hourly tariff profile forms the basis for evaluating the characteristics of the tariff itself, while the consumer simulation provides annual electricity costs for the different consumer archetypes. For flexible consumers, the model additionally determines the financial benefits obtained from adapting electricity consumption to the price signals.

   These outputs are subsequently used to calculate the quantitative evaluation indicators defined in Chapter 5, including cost recovery, consumer cost exposure, tariff volatility, tariff reflectiveness, economic incentives for flexibility, and interaction with other electricity-market signals.

7. **Flexibility benefits and congestion-response potential**
   The potential economic value of flexibility is determined by comparing consumer costs before and

after feasible demand adaptation. The available flexibility differs between assets and is therefore represented separately for EV charging, heat-pump demand, PV generation, and battery storage. Flexibility benefits are expressed as the reduction in consumer costs that can be achieved by responding to the applicable electricity price and grid tariff signals.

Within the current market-based modelling framework, physical congestion reduction is not calculated directly. Instead, the tariff-related flexibility benefit is used as an indicator of the strength of the financial incentive to respond to congestion-related grid tariffs. A higher tariff-related flexibility benefit therefore indicates greater economic potential for congestion-responsive behaviour. This measure should be interpreted as an indirect measure for congestion-reduction potential rather than as realised network relief.

7.4 Model output and application

The model generates the quantitative outputs required to evaluate the performance of the selected grid-tariff mechanism designs. These outputs include the hourly tariff profile, annual costs for each consumer archetype, flexibility benefits, optimised battery operation, and the potential effect of flexible behaviour on grid congestion.
These outputs are subsequently used to calculate the quantitative evaluation indicators defined in Chapter 5, including cost recovery, consumer cost exposure, tariff volatility, tariff reflectiveness, economic incentives for flexibility, the proxy for grid congestion reduction, and interaction with other electricity-market signals.

By applying the same input data and consumer archetypes to each grid-tariff mechanism, the model enables a consistent comparison of their system-level and consumer-level effects. The model thereby provides the quantitative basis for the evaluation and comparison of the alternative designs.

7.5 Input data

The model requires three main categories of input data: the transformer loading profile, consumer demand profiles, and electricity market prices. All input data are represented at an hourly resolution for the simulation year 2026.

Transformer loading profile
The transformer loading profile represents the network conditions on which the dynamic grid tariffs are based. Figure 3 shows the transformer load throughout the simulation year, including periods of high network utilisation and potential congestion. As complete measured data for the selected MSR were not yet available at the time of modelling, a synthetic but representative annual loading profile is used. The input series contains 8,760 hourly observations covering the full simulation year. The physical transformer has a rated capacity of 800 kW. In practice, a safety threshold of 50% is applied, corresponding to a loading level of 400 kW. However, under the available loading profile, applying this threshold would result in relatively limited congestion during the simulation period. Since the purpose of the model is to compare the behaviour and trade-offs of alternative tariff mechanisms under congestion conditions, the effective capacity parameter used for tariff generation is reduced to 400 kW. Applying the same 50% threshold results in a modelled congestion threshold of 200 kW. This adjustment should therefore be interpreted as a congestion-scenario assumption rather than as a representation of the physical transformer capacity. It increases the frequency and severity of congestion events sufficiently to evaluate how the alternative mechanisms respond under constrained network conditions. The sensitivity analysis subsequently examines how changes in network loading affect the resulting tariff levels, volatility, consumer costs, and DSO revenues.

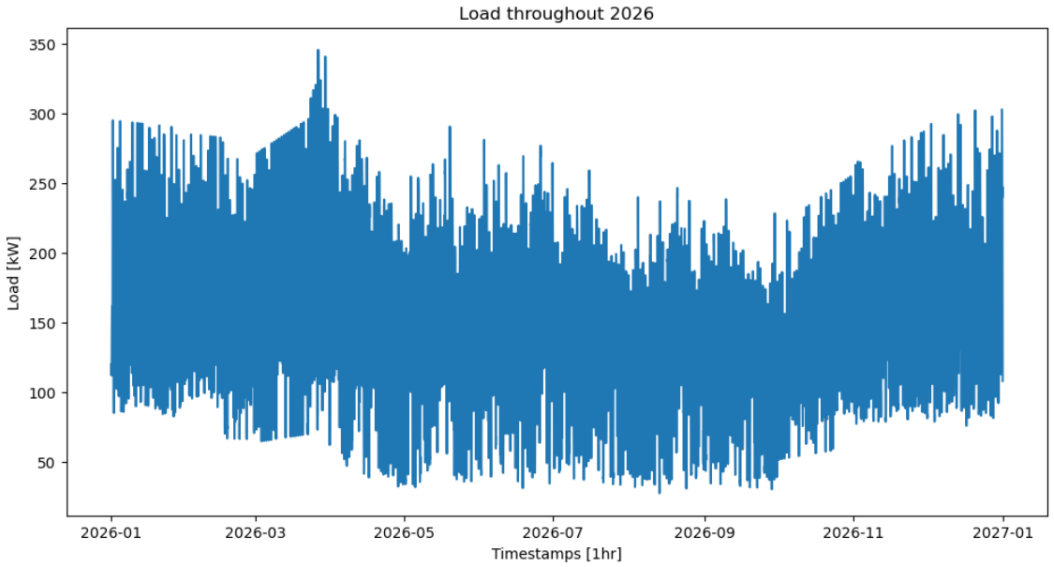

Figure 3: MSR load profile

Figure 3 shows recurring daily load patterns, reflecting differences between peak and off-peak hours. In addition, a clear seasonal pattern is visible, with lower average loading during summer and higher loading during winter. Several pronounced peaks occur around March and April, representing periods of exceptionally high network utilisation. These peaks are particularly relevant for the model, as they result in the strongest dynamic grid tariff signals.

Consumer demand profiles

The eight consumer archetypes are constructed from combinations of a base household demand profile and several flexible or distributed energy assets. The profiles are expressed as power in kilowatts (kW) on the y-axis and time on the x-axis. The following demand and generation profiles are used:

- **Base load:** represents household electricity demand excluding the additional assets considered in the model. Figure 4 shows recurring daily consumption peaks and a higher average demand during the winter months.

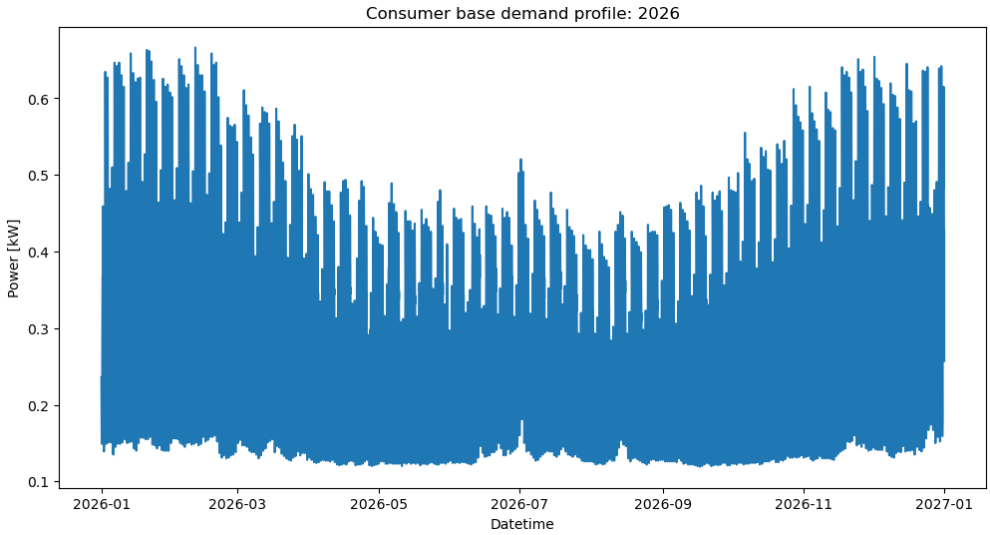

Figure 4: Base household demand profile

The recurring peaks reflect typical household consumption patterns throughout the day, while the seasonal variation represents the higher electricity demand generally observed during the colder months.

- **PV generation:** represents electricity generation from a residential PV system with an installed capacity of 4 kWp, which is representative of a typical Dutch residential installation (Verschoor, 2026).

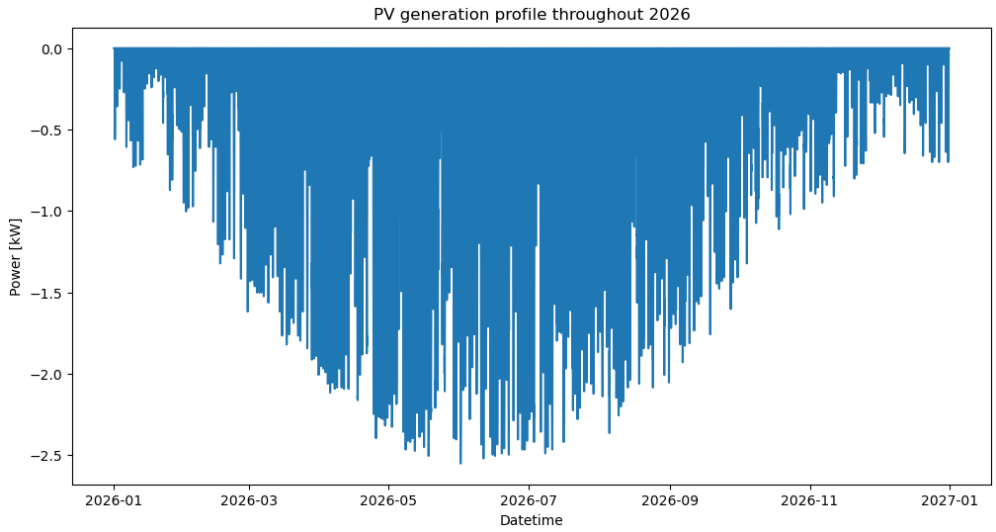

Figure 5: PV generation profile

As shown in Figure 5, PV generation is concentrated during daytime hours and is substantially higher during the summer months. The recurring daily pattern results from the absence of solar generation during nighttime. Negative values represent electricity generation and therefore injection into the grid rather than consumption. Annual PV generation is approximately 3,350 kWh.

- **EV charging:** represents the electricity demand associated with residential electric vehicle charging. An 11 kW home charging connection is assumed, which is a commonly used charging capacity for residential applications (Milieu Centraal, 2026b).

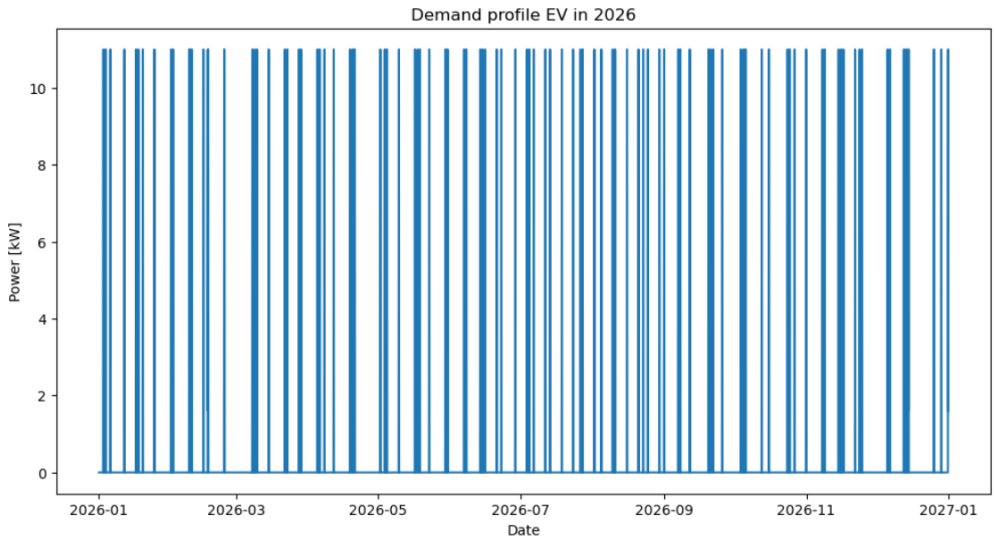

Figure 6: EV charging profile

Figure 6 shows the resulting EV charging profile. Annual charging demand is approximately 3,000 kWh. In contrast to PV generation and heat-pump demand, the profile shows little seasonal variation because EV charging demand is assumed to be largely independent of weather conditions. Charging occurs in relatively short periods with comparatively high power demand,

reflecting the typical behaviour of residential EV charging, where vehicles charge at or near their available charging capacity when connected.
Other demand patterns may also occur in practice, such as charging an EV using surplus PV generation. Such interactions between household assets are not explicitly represented in the input profiles used in this study. However, for the evaluation criterion *flexibility benefits*, flexible demand is optimised based on the combined electricity price and grid tariff. The resulting optimised demand patterns and associated benefits are presented in the following chapter.

- **Heat pump:** represents the electricity demand of a hybrid heat pump with a thermal capacity of approximately 3 kW, representative of a residential hybrid system (Milieu Centraal, 2026a).

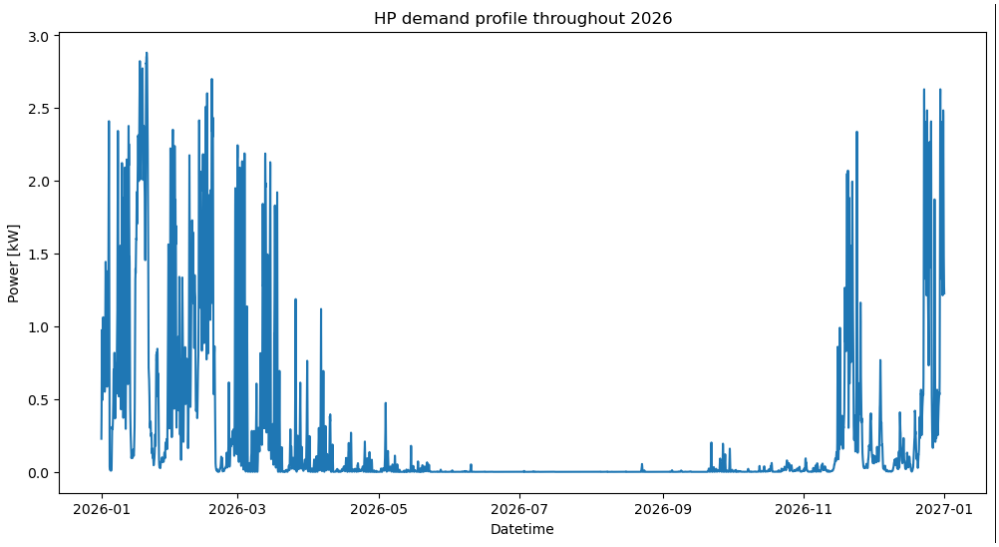

Figure 7: Heat-pump electricity demand profile

The profile in Figure 7 shows a strong seasonal pattern, with electricity consumption concentrated in the colder months. This is consistent with the temperature-dependent operation of a heat pump, for which heating demand increases as outdoor temperatures decrease. Short-term variations in demand result from differences in weather conditions and the intermittent operation of the heating system as the required indoor temperature is maintained. Annual electricity consumption is approximately 2,200 kWh.

- **Battery:** unlike the other assets, battery operation is not represented by a fixed input profile. Charging and discharging are optimised separately for each grid-tariff system based on electricity prices, grid tariffs, household demand, and PV generation. The resulting battery charging and discharging pattern is therefore an endogenous model output rather than an exogenous input.

Asset presence within the Stedin population
The consumer profiles used in the model represent households with different combinations of flexible and distributed energy assets. To provide context on the prevalence of these assets, data provided by Stedin are used. Across 2,167,997 connections, 664,503 PV installations, 148,979 home charging points, 156,911 heat pumps, and 30,843 residential batteries are registered. This corresponds to penetration rates of 30.65%, 6.87%, 7.24%, and 1.42%, respectively.

These figures provide information on the prevalence of individual assets, but not on their co-occurrence within households. For example, the data do not indicate how many households combine PV with an EV or heat pump. Since the adoption of these technologies is likely to be correlated, assuming statistical independence would introduce an uncertain estimate of the distribution of household types.

The available Stedin data provide information on the prevalence of individual assets, but do not identify how these assets are combined within individual households. Consequently, the distribution of the eight consumer profiles cannot be derived directly from the available data. For the population-level cost-recovery calculations, a base-case distribution is therefore assumed. This distribution should

be interpreted as a scenario used to provide a common population composition for comparing the mechanisms, rather than as an empirically observed representation of Stedin's customer population. The assumed base-case distribution is shown in Table 16.

Table 16: Base-case consumer profile distribution used for population-level cost recovery

Profile	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8
Share	30%	20%	10%	10%	10%	8%	7%	5%

For each mechanism, the annual tariff revenue associated with each consumer profile is combined using these population weights. The resulting weighted revenue per representative connection is subsequently scaled to the 2,167,997 connections in the Stedin population:

$$R_m^{\text{pop}} = N_{\text{conn}} \sum_{i=1}^{8} w_i R_{i,m},$$

where w_i represents the assumed population share of consumer profile i, $R_{i,m}$ is the annual tariff revenue associated with that profile under mechanism m, and N_{conn} is the total number of Stedin connections. The same population distribution is applied to all mechanisms to ensure a consistent comparison. Because the profile distribution is assumed rather than directly observed, its influence on aggregate cost recovery is examined separately in the sensitivity analysis in section 7.7.4.

Flexible asset profiles

To evaluate the potential benefits of demand-side flexibility, flexible variants of the EV and heat-pump profiles are constructed. The share of demand that can be shifted is defined through modelling assumptions based on the flexibility potential identified in the literature.

Flexibility benefits are calculated separately from the consumer cost-exposure analysis. The profiles used to calculate cost exposure do not include activated flexibility, except for CP8, which already includes optimised battery operation. The operational changes evaluated in the flexibility-benefit calculations are not incorporated into these profiles. For an individual asset whose flexibility is not already activated, the calculated total benefit represents the potential reduction in annual electricity costs when the evaluated flexible operation is implemented under the same reference conditions and tariff mechanism. However, separately calculated benefits are not necessarily additive when multiple assets operate flexibly together. For CP8, optimised battery operation is already reflected in the reported consumer costs, so the corresponding battery benefit should not be deducted again.

EV charging

EV charging provides temporal flexibility, as charging can generally be postponed provided that the required state of charge is reached before departure (Jansen, Gross, & Staffell, 2024). In the model, 40% of the EV charging energy of each day is treated as flexible, while the remaining 60% remains in the original charging hours. The flexible share is reallocated within the same day to the six hours with the lowest combined electricity price and grid tariff, subject to a maximum charging power of 11 kW. Total EV charging energy is conserved within each day. The shifted charging profile is only retained when it reduces the combined electricity and grid-tariff costs; otherwise, the original daily charging profile is maintained.

Heat pump

Heat pumps can provide demand-side flexibility by shifting part of their electricity consumption over time while maintaining indoor comfort. The available flexibility depends on seasonal heating requirements (Haupt et al., 2026). In the model, 40% of the daily heat-pump electricity demand is treated as flexible during December, January, and February, while 60% is treated as flexible during the remaining months. The non-flexible share remains in its original hours. Flexible electricity demand is reallocated only within the same day, starting with the hours with the lowest combined electricity price and grid tariff, subject to a maximum heat-pump load of 3 kW. Total daily heat-pump electricity consumption is conserved. The shifted profile is retained only when its combined electricity and grid-tariff costs do not exceed those of the original profile.

As flexible demand is shifted towards hours with lower combined electricity prices and grid tariffs, the resulting demand profile depends on the tariff structure of each mechanism design and therefore differs between designs.

PV curtailment
PV generation is treated as flexible through curtailment. Curtailment is applied only when PV generation exceeds household demand and the resulting surplus would otherwise be exported while the marginal value of export is negative. The export value is determined from the electricity market price, the applicable grid tariff, and the export costs. When both conditions are satisfied, the PV surplus is curtailed up to the point at which net export becomes zero for that hour. Curtailment therefore occurs only when avoiding export reduces the total electricity costs of the household.

Battery
The home battery included in the model represents a commonly sized residential battery system. It has a usable storage capacity of 11kWh and a maximum charging and discharging power of 3kW. The selected storage capacity falls within the range generally associated with residential battery systems, which may vary from approximately 2 to 20kWh depending on household demand and system configuration (Milieu Centraal, 2026c). The maximum charging and discharging power of 3kW is adopted as a modelling assumption representing a moderately sized residential inverter. Separate charging and discharging efficiencies of 95% are assumed, reflecting the upper end of the efficiency range reported for modern lithium-ion home batteries (Albert, 2026). Consequently, the model accounts for energy losses during both charging and discharging.
Battery operation is optimised at an hourly resolution against the combined electricity-price and grid-tariff signal. The State of Charge is constrained between 0 and 11 kWh, while charging and discharging are each limited to 3 kW. Separate charging and discharging efficiencies of 95% are applied. The initial State of Charge is set to 0 kWh and the final State of Charge is constrained to equal the initial State of Charge. This prevents the optimisation from obtaining an artificial financial benefit by ending the annual simulation with a depleted battery.

Electricity market prices
Hourly electricity market prices are included to account for the interaction between wholesale electricity prices and dynamic grid tariffs. For 2026, observed prices from 1 January to 12 August are used. As prices for the remainder of the year were not yet available, the remaining period is extrapolated using the temporal price patterns observed in 2025. The resulting annual price profile used in the simulations is shown in Figure 8.

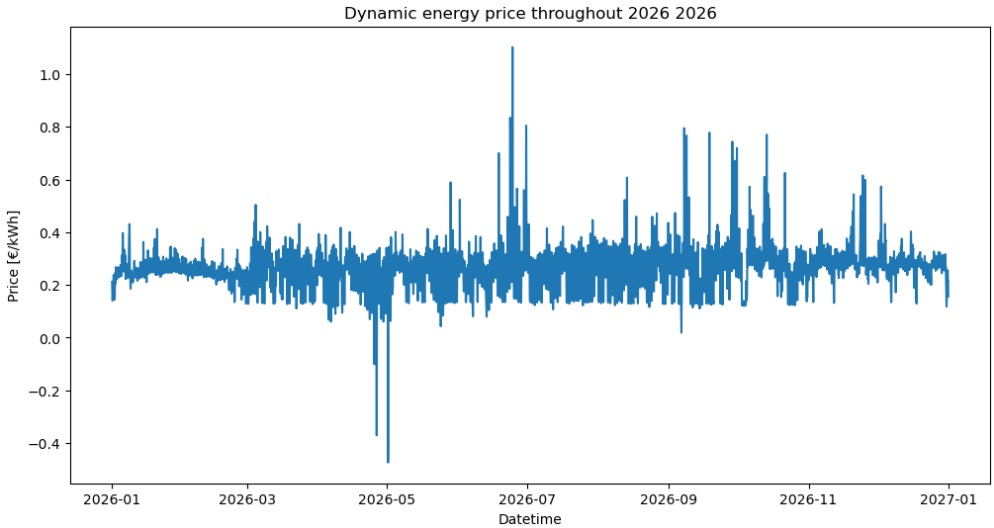

Figure 8: Electricity market price profile

Figure 8 shows recurring daily peaks, reflecting differences between peak and off-peak hours. Several more pronounced peaks can be observed in May and July. These may be associated with variations

in weather conditions and electricity demand behaviour. For example, sunny periods and high temperatures can influence local electricity generation and consumption patterns, leading to lower or higher prices (BNR, 2026).

7.6 Model verification

Model verification was performed to assess whether the implemented model behaves according to the intended calculation rules and technical constraints. The verification focused on three components: the calculation of the EmPower tariff, the implementation of mechanism-specific tariff rules, and the technical constraints applied to flexible consumer assets. The purpose of these tests is to verify the internal implementation of the model rather than to assess whether the model provides an accurate representation of real-world consumer behaviour.

7.6.1 Input and calculation verification

First, the calculation of the hourly EmPower tariff was independently reconstructed for five representative network conditions. The selected hours range from a situation without congestion to the hour with the highest observed congestion in the simulation. For each hour, the congestion factor and resulting tariff were manually recalculated using the tariff formulation described in Chapter 6 and compared with the tariff generated by the model.

Table 17 shows that the manually calculated tariffs are identical to the model output for all five selected conditions. In the absence of congestion, the tariff remains at the base level of 0.05 €/kWh. As congestion increases, the tariff increases accordingly, reaching 0.3776 €/kWh during the highest selected congestion condition. No numerical differences were observed between the independently reconstructed tariffs and the model output.

Table 17: Verification of the EmPower tariff calculation for representative congestion conditions

Scenario	Load (kW)	Safe capacity (kW)	Congestion (kW)	Congestion factor	Manual tariff (€/kWh)	Model tariff (€/kWh)
No congestion	120.060	200.0	0.000	0.00000	0.050000	0.050000
Minimum congestion	200.046	200.0	0.046	0.00023	0.050103	0.050103
Light congestion	212.542	200.0	12.542	0.06271	0.078219	0.078219
Medium congestion	226.860	200.0	26.860	0.13430	0.110435	0.110435
High congestion	345.604	200.0	145.604	0.72802	0.377609	0.377609

The identical results confirm that the implemented tariff-generation function correctly translates the congestion indicator into the corresponding EmPower tariff across different levels of network loading.

7.6.2 Mechanism-specific verification

In addition to the general tariff calculation, mechanism-specific verification tests were performed for Targeted EmPower, Flex Capacity, and the Adaptive Dynamic Tariff (ADT). These tests evaluate whether the implemented exposure rules correspond to the conceptual mechanism designs defined in Chapter 6.

For Targeted EmPower, Consumer Profile 1 was used because this profile consists only of base household demand and does not contain a targeted flexible asset. The effective tariff applied to this demand remained constant at 0.05 €/kWh throughout the simulation. The minimum and maximum observed effective tariffs were both 0.05 €/kWh, confirming that the dynamic congestion component is not applied to the base load under Targeted EmPower.

For the capacity-subscription mechanism, capacity exceedance was independently reconstructed as the difference between net electricity import and the subscribed capacity, bounded at zero. This reconstructed exceedance was compared with the model output for all eight consumer profiles. The tariff costs associated with exceedance were subsequently reconstructed by multiplying the exceedance by the applicable EmPower tariff. Both calculations correspond exactly to the model output. Furthermore, no EmPower tariff costs were assigned to consumption that remained within the subscribed capacity.

For ADT, tariff consistency was verified within each monthly tariff block. For every combination of month and tariff block (Off-peak, Normal, and Peak), the minimum and maximum tariff were compared. Each block contained only one unique tariff value and a tariff range of zero. This confirms that hourly tariff variation does not occur within an individual ADT block.

Table 18: Mechanism-specific model verification

Mechanism	**Verification test**	**Observed result**	**Outcome**
Targeted RTP	Dynamic congestion component should not be applied to the base household demand of CP1.	Minimum effective tariff = 0.05 €/kWh; maximum effective tariff = 0.05 €/kWh.	Passed
Flex Cap.	Capacity exceedance must equal max(net import − subscribed capacity, 0) and only this exceedance is exposed to the EmPower tariff.	For all eight profiles, reconstructed exceedance and tariff costs exactly matched the model. No tariff costs were assigned below the subscription threshold.	Passed
Adaptive Dynamic Tariff	The tariff should remain constant within each monthly Off-peak, Normal, and Peak block.	Each monthly tariff block contained one unique tariff value and a tariff range of zero.	Passed

For the capacity mechanism, CP1 and CP2 did not exceed their subscribed capacity during the simulation. CP3 and CP5–CP8 exceeded their subscribed capacity during 265 hours, while CP4 exceeded its subscription during 37 hours. In all cases, the implemented tariff calculation correctly distinguished between consumption within and above the subscribed capacity.

7.6.3 Flexible asset verification

Finally, the technical implementation of flexible consumer assets was verified. The tests focused on energy conservation and the technical constraints used for EV charging, heat-pump flexibility, and battery operation.

For EV charging, total annual electricity demand remained unchanged at 3,000kWh before and after flexibility activation. Energy conservation was additionally checked for every individual day, with a maximum observed daily difference of 0.0kWh. EV charging never exceeded the assumed maximum charging power of 11kW. Furthermore, the non-flexible share of 60% remained in the original charging hours, confirming that no more than the assumed 40% flexible share was shifted.

For the heat pump, electricity demand was also conserved on a daily basis. The maximum numerical difference between original and shifted daily consumption was approximately 7.1×10^{-15}kWh, which can be considered as zero. The optimised heat-pump load remained within the defined range of 0–3kW.

Battery operation was verified against its State-of-Charge (SoC), power, and efficiency constraints. The SoC remained within the specified storage boundaries throughout the simulation, while charging and discharging remained within the defined power limits. In addition, the hourly SoC transition was independently reconstructed using the assumed charging and discharging efficiencies. The resulting SoC values corresponded to those generated by the optimisation model, confirming that efficiency losses are correctly included in the battery balance.

Table 19: Verification of flexible-asset constraints

Asset	Verification test	Observed result	Outcome
EV	Annual and daily energy conservation	Original annual demand = 3,000kWh; flexible annual demand = 3,000kWh; maximum daily difference = 0.0kWh.	Passed
EV	Maximum charging power	Flexible EV charging never exceeded the 11kW charging limit.	Passed
EV	Maximum flexible share	The non-flexible 60% of EV demand remained in its original hours.	Passed
Heat pump	Daily energy conservation	Maximum daily energy difference = 7.1×10^{-15}kWh.	Passed
Heat pump	Power constraint	Flexible heat-pump demand remained between 0 and 3kW.	Passed
Battery	State-of-Charge and power constraints	The SoC remained within the specified storage bounds and charging/discharging remained within the applicable power limits.	Passed
Battery	Charging and discharging efficiency	Independent reconstruction of the SoC balance confirmed correct application of the specified efficiency losses.	Passed

The verification tests did not identify inconsistencies between the conceptual calculation rules and their implementation in the model. The tariff calculations, mechanism-specific exposure rules, and flexible-asset constraints therefore behave as intended within the tested conditions.

7.7 Model validation

7.7.1 Conceptual validation

Conceptual validation was performed by comparing selected model outcomes with the expected behaviour of the different tariff mechanisms. The purpose of this step is to assess whether the model produces results that are consistent with the underlying logic of the conceptual designs.

First, the static tariff is expected to provide no tariff-related incentive for flexibility, as the grid tariff does not vary over time. This is confirmed by Figure 19 in chapter 8, which shows zero grid-tariff flexibility benefits for consumers in the static tariff mechanism.

Second, the capacity-based subscription is expected to provide a stronger congestion-related flexibility incentive than the volumetric subscription, because consumers can reduce dynamic tariff exposure by avoiding capacity exceedance during high-tariff periods. This is reflected in Tables 31 and 32, where the capacity-based mechanism results in higher tariff flexibility benefits for the relevant flexible profiles.

Finally, the static tariff serves as the reference case for cost recovery. Consequently, the difference in tariff revenue relative to the reference should equal zero. Figure 17 confirms this expected result.

Validation implications

Overall, the conceptual validation supports the consistency between the model structure and the intended functioning of the tariff mechanisms. This provides a basis for comparing their effects within the defined scope, while the assumptions about network conditions and consumer behaviour remain relevant when interpreting the results.

7.7.2 Internal validation

Internal validation was performed by checking whether related model outputs are mutually consistent and whether changes in one part of the model lead to logically corresponding changes elsewhere. The

purpose of these tests is to identify internal contradictions that may not be detected by the calculation verification alone.

Validation during design
During model development, unexpected intermediate results were also used to identify implementation errors.

Curtailment benefits
One example concerned Indicator 5, economic incentives, for which flexibility benefits are calculated as the difference between consumer costs before and after flexibility is activated. The total flexibility benefit is defined as:

$$B_{\text{total}} = C_{\text{original}} - C_{\text{flexible}}, \tag{1}$$

where C_{original} represents annual costs before flexibility activation and C_{flexible} represents annual costs after flexibility activation. A positive value therefore represents a financial benefit from flexibility. The same calculation can be applied specifically to grid-tariff costs:

$$B_{\text{tariff}} = C_{\text{tariff,original}} - C_{\text{tariff,flexible}}. \tag{2}$$

An early model run for the PV profile produced an inconsistent result. The original annual costs for CP2 were €774.90, while the model calculated annual costs of €337.41 after applying PV flexibility. According to the equation above, this resulted in an apparent flexibility benefit of:

$$B_{\text{total}} = 774.90 - 337.41 = 437.49\ . \tag{3}$$

However, the same model run reported zero PV-curtailment hours and a total curtailed PV volume of 0.00 kWh. No flexibility had therefore actually been activated. The original and flexible electricity profiles should consequently have been identical, implying:

$$C_{\text{original}} = C_{\text{flexible}} \quad \Rightarrow \quad B_{\text{total}} = 0. \tag{4}$$

The reported benefit of €437.49 was therefore identified as an implementation error rather than an actual flexibility benefit. Inspection of the cost calculation showed that export-related costs and revenues were not treated consistently between the original and flexible cases. The sign convention for electricity export and the cost components included in both calculations were subsequently aligned, so that the reference and flexible profiles were evaluated using an identical cost definition. After this correction, zero activation of flexibility also resulted in zero flexibility benefit, as expected.

It should be noted that a negative value for an individual component of the flexibility benefit is not necessarily an error. Flexible assets respond to the combined electricity-price and grid-tariff signal. An action can therefore slightly increase grid-tariff costs while still reducing total consumer costs. For example, in the final Full EmPower results, PV flexibility results in a tariff-specific benefit of approximately €-2.24, while the total financial benefit remains positive at approximately €5.54. The relevant consistency condition is therefore that cost-minimising flexibility does not increase total costs, rather than requiring every individual cost component to decrease.

Flexibility optimisation

A second correction was made during the construction of the flexibility optimisation. In an earlier version of the model, flexible electricity demand was primarily optimised in response to the dynamic grid tariff. The optimisation therefore attempted to shift electricity consumption towards hours with lower grid tariffs, without fully accounting for the electricity market price faced by the consumer.

This formulation was incomplete from the consumer perspective. A consumer does not respond to the grid tariff in isolation, but to the combined financial effect of the electricity price and the grid tariff. An hour with a low grid tariff may, for example, coincide with a relatively high electricity price. Shifting flexible demand towards such an hour could therefore reduce grid-tariff costs while increasing total electricity costs. Consequently, an optimisation based only on the grid tariff could produce a load

schedule that was favourable from the perspective of the network tariff but not financially optimal for the consumer.

The initial optimisation objective can conceptually be represented as:

$$\min \sum_t P_t \cdot T_t, \tag{5}$$

where P_t represents electricity consumption and T_t the applicable grid tariff. During model development, the objective was therefore extended to include the electricity market price:

$$\min \sum_t P_t \cdot (T_t + E_t)\,, \tag{6}$$

where E_t represents the hourly electricity price. The detailed cost formulation additionally accounts for electricity import and export where applicable.

After this adjustment, flexible assets were optimised against the combined price signal actually experienced by the consumer. As a result, the model no longer assumed that the lowest grid-tariff hours were necessarily the financially most attractive hours. This correction was particularly relevant for the EV, heat-pump, and battery flexibility calculations and ensured that the calculated flexibility benefits represent reductions in total consumer costs rather than reductions in grid-tariff costs alone.

Ex-post validation
Higher congestion levels should result in higher EmPower tariffs. The representative tariff calculations show a linear increase in the tariff as congestion intensity increases, from the base tariff of 0.05 €/kWh without congestion to 0.3776 €/kWh under the highest selected congestion condition. This behaviour is internally consistent with the tariff-generation logic.

Consumer profiles with greater electricity import during congestion periods should face higher annual grid-tariff costs under Full EmPower. The model results show that high-demand profiles generally experience higher tariff costs, while profiles with lower demand or substantial PV generation face lower costs. This is consistent with the underlying exposure calculation.

The flexibility optimisation is formulated as a cost-minimisation problem. Consequently, activating available flexibility should not increase the total costs of the optimised consumer relative to the original profile. Across the evaluated flexibility cases, the calculated flexibility benefits are non-negative, confirming that the optimisation does not produce financially inferior solutions.

The Ex-post Bonus mechanism is designed to restore aggregate tariff revenue after the dynamic tariff has been applied. The model results in figure 17 show that the population-weighted tariff revenue difference is restored to approximately zero after the ex-post correction. This confirms consistency between the settlement rule and the reported cost-recovery outcome. In addition, the consumer costs show a drop in the final timestep, when the bonus is distributed. This also matches the expectations.

No internal contradictions were identified between the related model outputs. The calculated tariffs, consumer costs, flexibility outcomes, exposure rules, and settlement results therefore show mutually consistent behaviour across the evaluated mechanisms.

Validation implications
The internal validation supports the consistency of the calculated outcomes with the model's accounting relationships and expected mechanism behaviour. These checks strengthen confidence in the comparisons presented in Chapter 8, but do not establish how accurately the model represents real-world outcomes.

7.7.3 Extreme values test

Extreme-value tests were performed to assess whether the model responds logically when key tariff parameters are assigned values far outside their normal operating range. The purpose of these tests is

not to represent realistic tariff scenarios, but to determine whether the model behaves consistently at the boundaries of the parameter space.

EmPower tariff: dynamic component
First, the dynamic tariff component was set to −1000, 0, and +1000. These values respectively reverse the congestion-related price signal, remove the dynamic component entirely, and strongly amplify the congestion signal. The resulting tariff characteristics and PV curtailment response are presented in Table 20.

Table 20: Extreme-value validation of the dynamic tariff component

Dynamic tariff component	Minimum tariff	Maximum tariff	Tariff–congestion correlation	Curtailed PV (kWh)	Curtailment hours
−1000	-727.97	0.05	-1.00	0.00	0
0	0.05	0.05	0.00	0.00	0
+1000	0.05	728.07	1.00	44.81	26

The results show the expected model behaviour under all three extreme configurations. With a dynamic tariff component of −1000, the relationship between congestion and the tariff is fully reversed. The tariff–congestion correlation becomes −1.00, while the minimum tariff decreases to -727.97 €/kWh. Under these conditions, no PV curtailment occurs, which is consistent with the absence of a positive congestion-related incentive to reduce electricity injection.

When the dynamic tariff component is set to zero, the tariff remains constant at the base level of 0.05 €/kWh throughout the simulation. Consequently, the correlation between congestion and the tariff approaches zero and no PV curtailment occurs. This confirms that all congestion-related tariff variation disappears when the dynamic tariff component is removed.

Finally, setting the dynamic tariff component to +1000 strongly amplifies the congestion signal. The maximum tariff increases to 728.07 €/kWh and the tariff–congestion correlation equals 1.00. In response to this extreme positive congestion signal, 44.81kWh of PV generation is curtailed across 26 hours. This indicates that the flexibility logic responds in the expected direction when the congestion-related tariff becomes strongly unfavourable.

Together, these tests confirm that both the tariff-generation function and the associated PV flexibility response behave consistently when the dynamic tariff parameter is reversed, removed, or strongly amplified.

Network capacity
A second extreme-value test was performed by varying the available network capacity while keeping the electricity demand profile unchanged. The purpose of this test is to assess whether changes in the physical network constraint propagate consistently through the congestion calculation and the resulting tariff signal. Two extreme boundary conditions were considered: an effectively zero network capacity of 0.0001 kW and a practically unconstrained network capacity of 100,000 kW. An exact value of 0 kW was avoided because the tariff formulation normalises congestion by the available capacity range, which would result in division by zero.

The results are presented in Table 21. Under the effectively zero-capacity scenario, congestion occurs during all 8,760 hours of the year. The tariff remains constant at 0.50 €/kWh, which corresponds to the maximum tariff level resulting from the bounded congestion factor. The tariff standard deviation is therefore zero. The tariff–congestion correlation is undefined in this scenario because the tariff is constant throughout the simulation.

At the opposite boundary, a network capacity of 100,000 kW completely eliminates congestion. No congestion hours are observed and the tariff remains at the base level of 0.05 €/kWh throughout the year. Again, the tariff standard deviation is effectively zero and the tariff/congestion correlation is undefined because both congestion and the tariff show no relevant temporal variation.

Table 21: Extreme-value validation of network capacity

Indicator	**Capacity = 0.0001 kW**	**Capacity = 100,000 kW**
Congestion hours	8,760	0
Share of congestion hours (%)	100.00	0.00
Maximum congestion (kW)	345.60	0.00
Mean congestion during congested hours (kW)	143.00	0.00
Minimum tariff (€/kWh)	0.50	0.05
Maximum tariff (€/kWh)	0.50	0.05
Mean tariff (€/kWh)	0.50	0.05
Tariff standard deviation (€/kWh)	0.00	0.00
Tariff–congestion correlation	N/A	N/A

The extreme-capacity scenarios therefore show the expected boundary behaviour. When available network capacity approaches zero, the model classifies all hours as congested and applies the maximum congestion-related tariff. When network capacity is effectively unconstrained, congestion disappears and the tariff remains at its base level. This confirms that the network-capacity input is propagated consistently through the congestion and tariff calculations.

Test implications

The extreme-value tests show that the model reproduces the expected boundary behaviour under very low and very high network capacity. This supports the consistency of the congestion and tariff calculations at these limits, while the sensitivity analysis below examines how the outcomes change under less extreme variations in the input assumptions.

7.7.4 Sensitivity analysis

A sensitivity analysis is performed to assess how changes in key input assumptions affect the model results. Two input variables are varied: electricity demand and the assumed consumer profile distribution. Electricity demand is included because future electrification is expected to increase network loading, while the population distribution is tested because the assumed shares of consumer profiles directly affect the aggregate financial outcomes for Stedin.

Demand

Five demand scenarios are evaluated: −10%, the base case, +10%, +25%, and +50%. The hourly network demand profile is scaled uniformly for each scenario, while all other model inputs and tariff parameters are kept unchanged. The resulting effects on congestion frequency, tariff volatility, consumer cost exposure, and Stedin's cost recovery are then compared with the base case.

Figure 9 shows the tariff duration curves for the five demand scenarios.

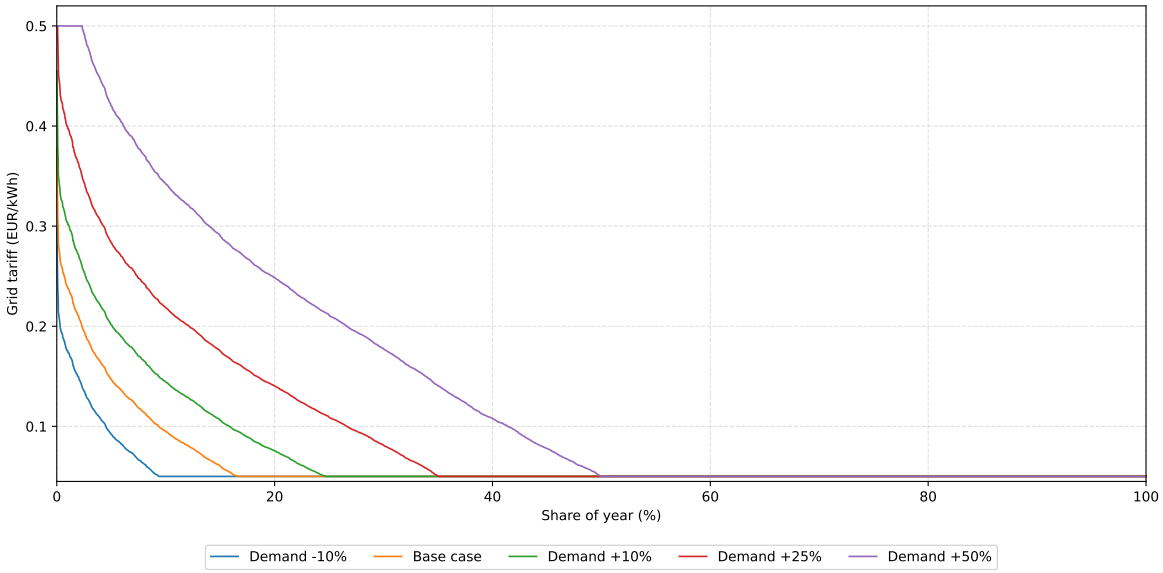

Figure 9: Tariff duration curves under alternative electricity demand scenarios.

As expected, higher electricity demand results in a larger share of hours with elevated grid tariffs. The tariff duration curves show that both the frequency and magnitude of high-tariff periods increase as demand rises. This effect is also reflected in the number of congestion hours in each scenario, presented in Table 22.

Table 22: Sensitivity of congestion frequency to changes in electricity demand

Demand scenario	**Congestion hours**	**Share of year (%)**
−10%	819	9.35
Base case	1,456	16.62
+10%	2,160	24.66
+25%	3,076	35.11
+50%	4,375	49.94

Figure 9 and Table 22 show a clear positive relationship between electricity demand, congestion frequency, and tariff levels. Increasing demand causes more hours to exceed the congestion threshold, which in turn activates the congestion-related tariff component more frequently and at higher levels. No unexpected or discontinuous model behaviour is observed. The results therefore indicate that the model responds consistently to changes in network demand, although the magnitude of the resulting tariff and financial outcomes is sensitive to the assumed demand level.

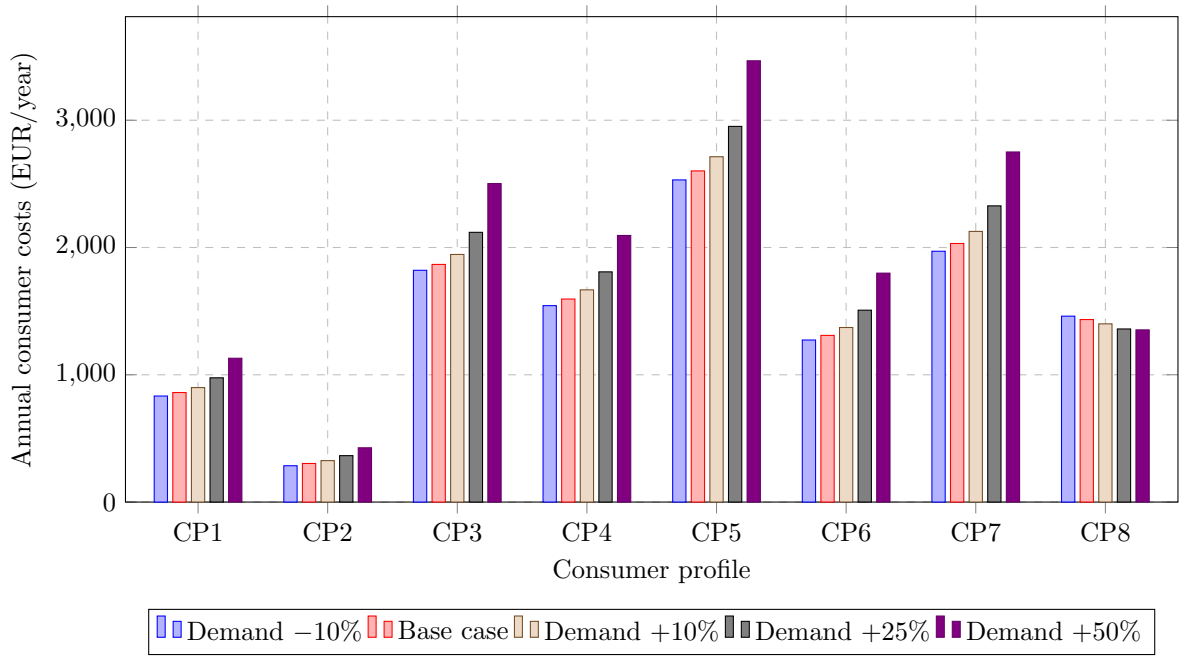

Figure 10: Sensitivity of annual consumer costs to changes in electricity demand.

Figure 10 shows the effect of changing network demand on annual consumer costs. Consumer profiles with relatively limited exposure to the dynamic tariff are less strongly affected by changes in network demand. In contrast, the annual costs of CP3–CP7 increase substantially under the higher-demand scenarios. These profiles have relatively large electricity imports and therefore experience greater financial exposure when congestion occurs more frequently and tariff levels increase.

This result is consistent with the cost-exposure results presented earlier in the analysis, which show that tariff costs constitute a relatively important component of the annual costs of these profiles. As network demand increases, more hours become congested and the dynamic tariff component is activated more frequently. Consequently, consumers importing electricity during these periods face higher annual tariff costs.

CP8 shows a different pattern, with annual costs remaining relatively stable and eventually decreasing under the higher-demand scenarios. This profile contains several flexible assets, including battery storage, and therefore has greater opportunities to respond to stronger differences in tariff levels. The result illustrates that the financial effect of increasing congestion depends not only on total electricity consumption, but also on the flexibility available to the consumer.

Overall, the observed changes in consumer costs are consistent with the expected functioning of the model. Profiles with greater tariff exposure become more strongly affected when network demand and congestion increase, while profiles with greater flexibility have more opportunities to mitigate these effects.

Table 23: Sensitivity of tariff volatility to changes in electricity demand

Demand scenario	Mean	Std. dev.	CoV	Min.	Max.	Range	Extreme hours	Share (%)
−10%	0.055492	0.022094	0.398146	0.050000	0.299848	0.249848	395	4.51
Base case	0.062518	0.037203	0.595078	0.050000	0.377609	0.327609	513	5.86
+10%	0.072994	0.054434	0.745723	0.050000	0.455370	0.405370	573	6.54
+25%	0.094523	0.082316	0.870855	0.050000	0.500000	0.450000	585	6.68
+50%	0.140098	0.126549	0.903292	0.050000	0.500000	0.450000	573	6.54

Table 23 shows that tariff volatility increases as network demand rises. Between the −10% and +25% demand scenarios, both the standard deviation and the coefficient of variation increase substantially. This indicates that higher network demand results in a wider distribution of tariff levels and therefore

greater tariff volatility.

The number of extreme tariff hours also increases between the −10% and +25% scenarios. However, the +50% demand scenario results in a slight reduction in the number of hours classified as extreme. This does not imply that tariff volatility decreases. Extreme tariff hours are defined relative to the scenario-specific mean and standard deviation. As demand increases, both the mean tariff and its standard deviation increase, which also raises the threshold above which a tariff is classified as extreme. At the same time, the tariff is capped at EUR 0.50/kWh. Consequently, an increasing number of hours approach or reach the tariff cap, while the statistical threshold for classification as an extreme value also increases. This explains why the number of extreme hours decreases slightly between the +25% and +50% scenarios despite the overall increase in tariff levels.

The coefficient of variation increases from 0.398 in the −10% scenario to 0.903 in the +50% scenario. Higher demand causes more hours to move away from the base tariff of EUR 0.05/kWh towards higher congestion-related tariff levels. The resulting increase in dispersion is proportionally larger than the increase in the mean tariff, leading to a higher coefficient of variation. The monotonic increase in the CoV therefore reflects the expected relationship between increasing network demand, more frequent congestion, and greater tariff volatility.

Table 24 shows how changes in network demand affect Stedin's cost recovery.

Table 24: Sensitivity of cost recovery to changes in electricity demand

Demand scenario	Average difference per connection (EUR)	Total tariff income difference (EUR)
−10%	-169.46	-367 million
Base case	-136.63	-296 million
+10%	-86.37	-187 million
+25%	20.09	43 million
+50%	245.92	533 million

The results in Table 24 show that Stedin's tariff revenues increase substantially as network demand rises. Under lower-demand conditions, the dynamic tariff generates considerably less revenue than the static reference case. As demand increases, this revenue shortfall decreases and eventually turns into a revenue surplus between the +10% and +25% demand scenarios.

The relationship between demand and tariff revenue is non-linear. Increasing demand does not affect tariff revenues proportionally because the dynamic tariff only increases once network loading exceeds the congestion threshold. Additional demand during hours that remain below this threshold does not activate the congestion-related tariff component. Once the threshold is crossed, however, the tariff increases with congestion intensity. As demand rises further, an increasing number of hours cross this threshold and therefore contribute to higher tariff revenues.

This effect becomes particularly visible in the +50% demand scenario, in which 4,375 hours are classified as congested, compared with 3,076 hours in the +25% scenario and 1,456 hours in the base case, as shown in Table 22. The strong increase in congested hours explains why tariff revenues increase disproportionately under the highest-demand scenario. The cost-recovery results therefore show that the financial performance of the tariff mechanism is strongly dependent on the assumed level of network demand.

Population distribution

The aggregate cost recovery for Stedin depends on the assumed distribution of consumer profiles across the population. Although Stedin data provide information on the penetration of individual assets, their co-occurrence within households is unknown. The consumer profile distribution therefore remains an assumption and may differ substantially between neighbourhoods or change over time as the adoption of EVs, heat pumps, PV systems, and batteries increases. To assess the sensitivity of the cost-recovery results to this assumption, three population scenarios are considered: the base-case distribution, a

low-asset penetration scenario, and a high-asset penetration scenario. The corresponding profile weights are shown in Table 25.

Table 25: Consumer profile distributions used in the sensitivity analysis

Scenario	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8
Low-asset penetration	40%	30%	7%	7%	6%	4%	3%	3%
Base case	30%	20%	10%	10%	10%	8%	7%	5%
High-asset penetration	15%	10%	12%	12%	15%	13%	12%	11%

Table 26: Sensitivity of Stedin cost recovery to the assumed consumer profile distribution

Population scenario	Full EmPower (EUR)	EmPower Flex Capacity (EUR)
Low-asset population	-397 million	-70 million
Base distribution	-296 million	20 million
High-asset population	-195 million	111 million

Table 26 shows that Stedin's cost recovery increases as the share of asset-rich consumer profiles increases. Under Full EmPower, all three population scenarios result in a revenue shortfall compared with the static reference case. However, this shortfall decreases from approximately €397 million in the low-asset scenario to €195 million in the high-asset scenario. This is mainly because asset-rich profiles generally have higher electricity demand and therefore generate more tariff revenue under dynamic pricing.

EmPower Flex Capacity shows the same overall relationship, but remains considerably closer to revenue neutrality. The low-asset scenario results in a revenue shortfall of approximately €70 million, while the base and high-asset scenarios result in surpluses of approximately €20 million and €111 million, respectively. The higher revenues in asset-rich scenarios can be explained by the greater contribution of profiles with higher subscription levels and greater potential capacity exceedance.

The results therefore show that aggregate cost recovery is sensitive to the assumed consumer profile distribution. However, EmPower Flex Capacity remains substantially closer to the static reference revenue than Full EmPower across all three population scenarios. This indicates that the favourable cost-recovery performance of the capacity-based mechanism is relatively robust to changes in the assumed population composition.

Sensitivity analysis synthesis

Taken together, the sensitivity tests show that the financial outcomes depend on both network demand and consumer population composition. Higher network demand increases congestion frequency, tariff variation, and aggregate revenues, while its effect on household costs differs between profiles. If future electrification increases network loading without corresponding capacity expansion, mechanisms that retain congestion-related incentives while limiting consumer exposure may therefore become increasingly relevant. This strengthens the motivation for evaluating such designs, although their performance under future conditions requires further assessment. Changes in population composition also affect revenue recovery: Flex Capacity remains closer to the Static reference than Full EmPower across the tested population scenarios, but does not consistently achieve revenue neutrality. The results in Chapter 8 should therefore be interpreted as a comparison under shared base-case assumptions, rather than as forecasts of household costs or DSO revenues. Chapter 9 draws on these sensitivities when assessing the design trade-offs, particularly the dependence of revenue recovery on subscription calibration and the consumer population.

8 Results

This chapter presents the quantitative results for the evaluated grid-tariff mechanisms, organised by criterion to facilitate comparison between designs. It first illustrates the tariff patterns, followed by consumer cost exposure, tariff volatility, cost recovery, and congestion reflectiveness. The economic incentive results distinguish total flexibility benefits, congestion-related financial incentives, and effective tariff burden. The chapter then examines the interaction with electricity-price signals and concludes with a synthesis of the main findings. Static serves as the reference where applicable. Chapter 9 evaluates the resulting trade-offs alongside the qualitative criteria.

8.1 Tariff pattern

This subsection illustrates the two distinct underlying tariff patterns: the hourly EmPower signal and the block-based Adaptive Dynamic Tariff (ADT). Annual profiles show seasonal variation, while a daily ADT profile illustrates the arrangement of tariff blocks within a day.

EmPower
Figure 11 shows the hourly Full EmPower tariff throughout the simulated year.

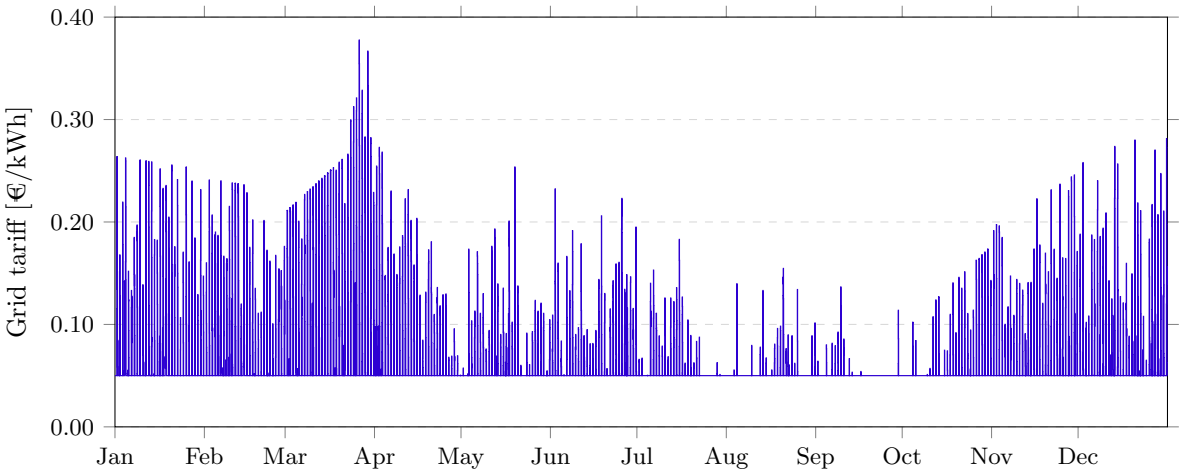

Figure 11: Hourly grid tariff under Full EmPower in the base-case simulation.

The Full EmPower tariff varies hourly, with frequent fluctuations between the base tariff and higher congestion-dependent levels. Tariffs are generally higher during winter and early spring, with the largest peak occurring in March. During summer, the tariff frequently remains at the base level of 0.05 €/kWh, interrupted by occasional increases. The Ex-post Bonus retains this hourly pattern but applies a higher base tariff; a separate tariff-pattern figure is therefore omitted.

ADT
Figure 12 shows the annual ADT profile, while Figure 13 illustrates the daily tariff schedule on 1 January.

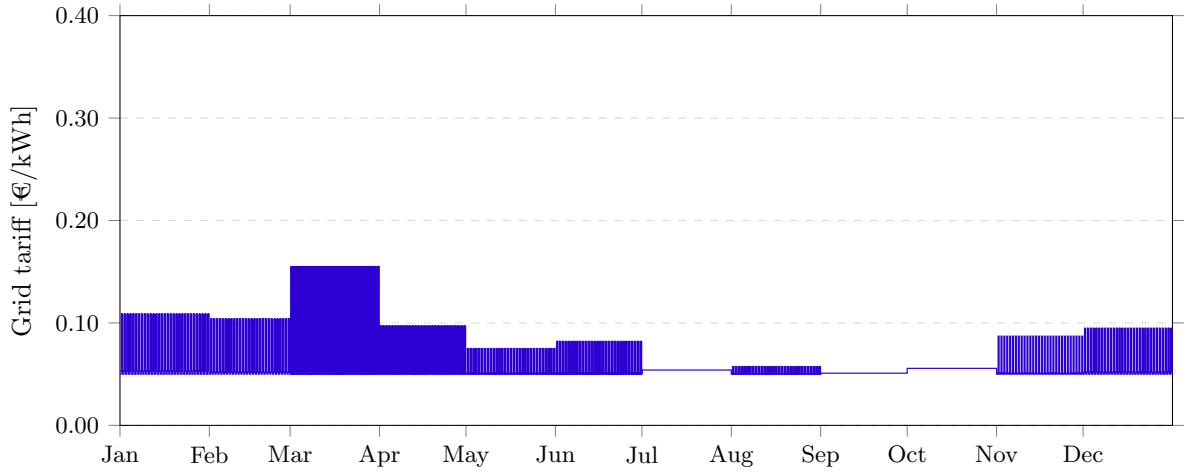

Figure 12: Hourly grid tariff under the Adaptive Dynamic Tariff in the base-case simulation. The vertical scale is identical to the Full EmPower figure to facilitate comparison.

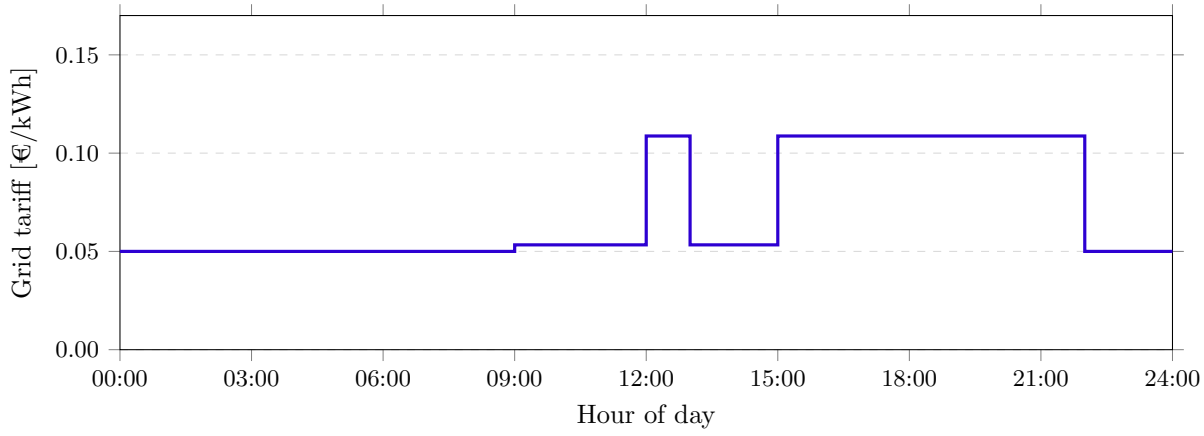

Figure 13: ADT tariff schedule for the first day of January in the base-case simulation. A narrower vertical scale is used to show the tariff differences between hours.

ADT replaces hourly tariff fluctuations with predefined time blocks. The block schedule and corresponding tariff levels remain fixed within each month. The annual pattern retains higher tariff levels during winter and early spring and lower levels during summer, while showing substantially less variation than Full EmPower. The highest ADT block tariff occurs in March, coinciding with the period containing the highest Full EmPower peak. The identical vertical scales facilitate comparison between the annual profiles.

The daily profile for 1 January shows three tariff levels: the base level overnight and late in the evening, an intermediate level during parts of the day, and the highest level around midday and from the afternoon into the evening. The tariff remains constant within each block, and the same daily schedule applies throughout January.

Although the ADT profile visually suggests lower tariff levels, its annual mean is identical to that of Full EmPower, as shown in Table 59. Averaging the underlying hourly tariffs into predefined blocks reduces high peaks while raising some lower hourly values, preserving the annual mean. The maximum tariff decreases from 0.37761 €/kWh under Full EmPower to 0.15507 €/kWh under ADT. The apparent difference therefore reflects reduced tariff variation rather than a lower average tariff level.

8.2 Cost exposure

This subsection compares changes in total annual electricity costs across the evaluated consumer profiles relative to the Static tariff. An overview of all mechanisms is followed by a more detailed examination of Full EmPower, Flex Capacity, and ADT. The underlying profile-level cost data are provided in Appendix F.

The consumer cost results show how the alternative mechanisms affect total annual electricity costs across the eight household profiles relative to the Static tariff. Figure 14 presents the mean change and the range across these profiles. Each profile receives equal weight, so the mean describes the modelled household archetypes rather than the actual consumer population. The detailed results below distinguish changes in grid-tariff costs from changes in total electricity costs.

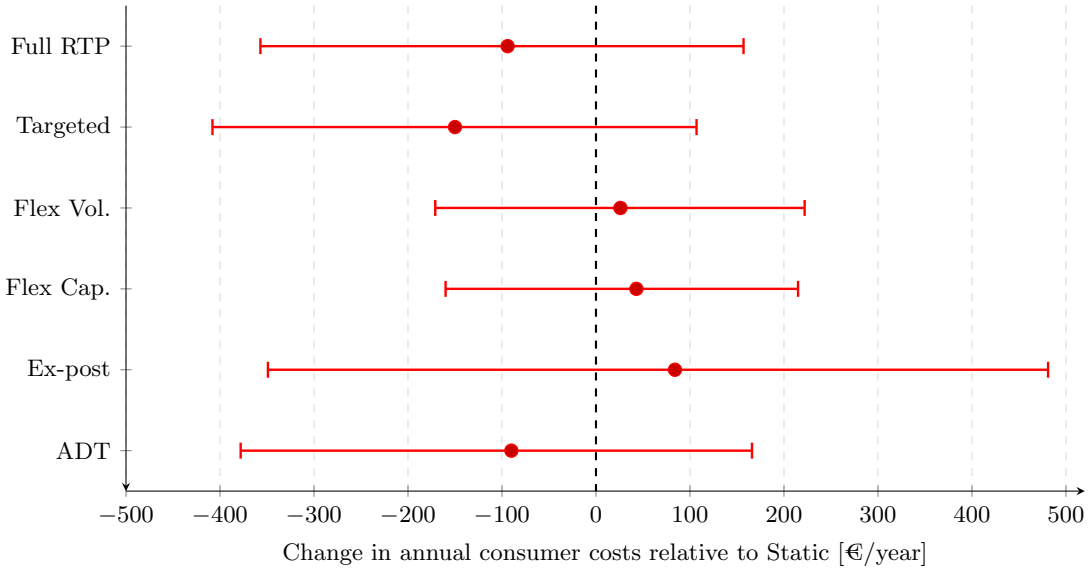

Figure 14: Consumer cost exposure for the alternative grid-tariff mechanisms. Points indicate the mean annual change in consumer costs relative to the Static tariff, while the horizontal ranges represent the minimum and maximum changes across the evaluated consumer profiles. Negative values indicate lower annual costs relative to the Static tariff.

Figure 14 shows that Full EmPower, Targeted EmPower, and ADT produce lower average total electricity costs than Static across the evaluated profiles. Targeted EmPower shows the largest average reduction, while Full EmPower and ADT produce similar average outcomes. Flex Volumetric and Flex Capacity show smaller positive average changes, but their ranges indicate that some profiles benefit while others face higher costs. Ex-post Bonus also produces a positive average change and shows the widest range of outcomes. Revenue neutrality does not imply a zero mean in this figure: cost recovery concerns grid-tariff revenues weighted by population shares, whereas this figure shows equally weighted changes in total electricity costs.

Ex-post Bonus produces the largest spread between profiles, with annual grid-tariff changes ranging from approximately €349 below to €481 above Static. Its higher base tariff and subsequent uniform rebate therefore result in substantial redistribution relative to Static. Restoring aggregate reference revenues does not make the financial outcome neutral for individual households.

Three mechanisms are examined in more detail because they illustrate distinct consumer cost outcomes. Full EmPower produces a wide range of cost changes and relatively low average consumer costs, making it particularly relevant to examine as the basis of Stedin's proposed design. Flex Capacity results in higher average costs than Full EmPower, while ADT produces comparable average outcomes despite its different tariff structure.

EmPower

Figure 15 compares annual electricity costs under Full EmPower with the Static reference for each consumer profile, distinguishing grid-tariff costs from other electricity costs. Table 27 reports the corresponding changes in grid-tariff costs and percentage changes in total electricity costs.

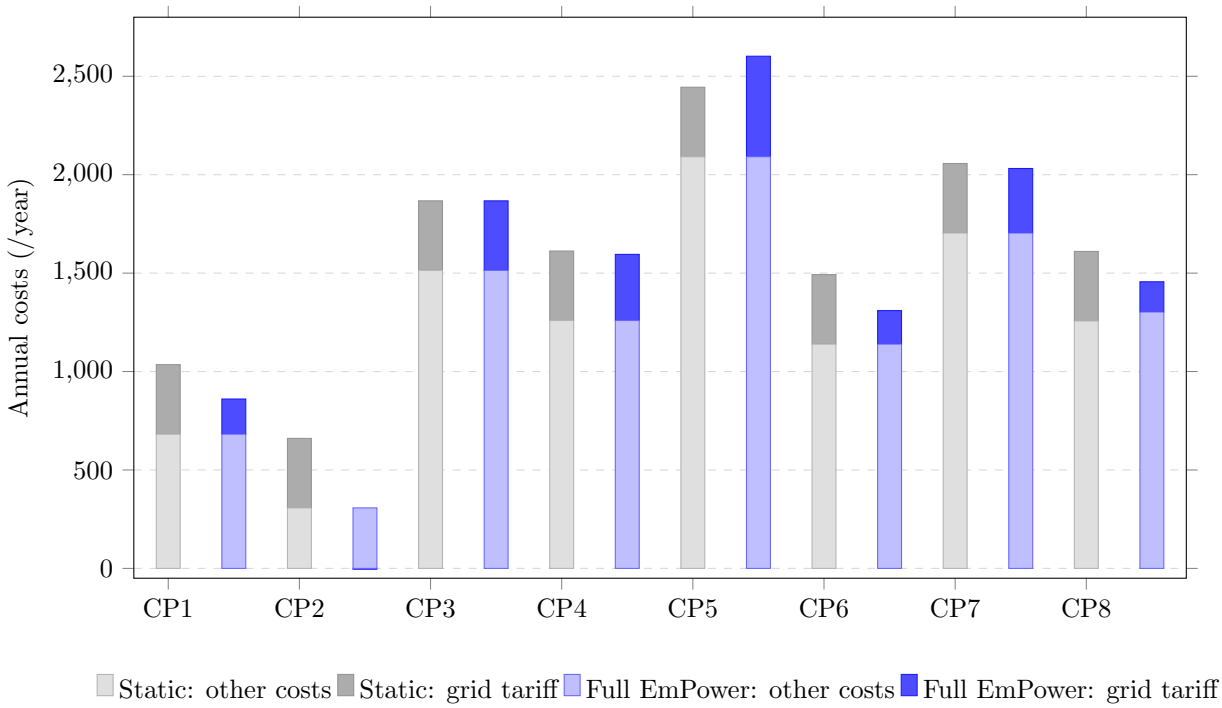

Figure 15: Annual consumer cost exposure under Full EmPower compared with the static reference case. Each bar shows total annual electricity costs, separated into grid tariff costs and other electricity costs.

Figure 15 is shown for Full EmPower to provide an overview of the relative contributions of grid-tariff costs and other electricity costs to the annual bill. The subsequent comparisons focus on tabulated cost changes rather than repeating this breakdown for each mechanism.

Table 27: Relative change in consumer costs under Full EmPower compared with the static reference case

Profile	**Δ tariff costs ()**	**Δ total costs (%)**
CP1	-174.55	-16.86
CP2	-357.33	-54.11
CP3	-0.01	0.00
CP4	-16.99	-1.05
CP5	157.50	6.44
CP6	-182.84	-12.25
CP7	-25.28	-1.23
CP8	-199.60	-9.58

Figure 15 and Table 27 show that Full EmPower reduces annual grid-tariff costs for most profiles. CP2 experiences the largest reduction, at €357.33, corresponding to a 54.11% decrease in total electricity costs. CP1, CP6, and CP8 also show substantial tariff-cost reductions. CP3 remains approximately unchanged, while CP5 is the only profile with higher grid-tariff costs: an increase of €157.50, equivalent to a 6.44% increase in total electricity costs.

CP5 combines an EV and a heat pump and has the highest total annual electricity costs among the evaluated profiles under Full EmPower. Both assets also offer opportunities to reduce these costs

through flexible operation, which is not activated in the CP5 profile used for this comparison. The separately calculated EV and heat-pump flexibility benefits illustrate this potential, although their combined benefit for CP5 has not been quantified.

These differences reflect the replacement of a fixed annual charge with charges linked to the volume and timing of electricity exchange. The outcomes therefore depend on the household's consumption and generation pattern, rather than annual demand alone. Targeted EmPower further reduces grid-tariff costs by approximately €50.27 for each modelled profile relative to Full EmPower, while retaining differences between profiles.

Flex Cap.

Table 28 shows the change in cost exposure for the eight consumer profiles compared to the static case under the Flex-Capacity mechanism.

Table 28: Change in consumer costs under EmPower Flex Capacity compared with Static case

Profile	**Δ tariff costs ()**	**Δ total costs (%)**
CP1	-41.03	-3.96
CP2	-159.87	-24.21
CP3	+208.89	+11.19
CP4	+8.02	+0.50
CP5	+214.67	+8.78
CP6	+89.96	+6.03
CP7	+100.23	+4.87
CP8	-79.02	+0.95

Table 28 shows that Flex Capacity produces higher annual grid-tariff costs for CP3–CP7 than Static, while CP1, CP2, and CP8 pay less. The largest increases occur for CP3 and CP5, at €208.89 and €214.67, respectively. Both profiles include an EV, and CP5 also includes a heat pump. In contrast, CP4, which includes a heat pump but no EV, remains close to the reference case, with an increase of €8.02. These outcomes reflect the combined effects of subscription fees, charges for capacity exceedance, and grid-tariff remuneration for exports.

The relatively large increases for CP3 and CP5 highlight the relevance of EV charging schedules under a capacity-based subscription. Concentrated charging demand can exceed the subscribed capacity, while smart charging offers opportunities to reduce these charges. Such flexibility is not activated in the EV profiles used for the cost-exposure comparison. However, EV ownership alone does not determine the outcome: CP6–CP8 also include an EV, but their PV generation and, for CP8, optimised battery operation affect imports, exports, and the resulting tariff costs.

CP8 further illustrates why grid-tariff costs and total electricity costs must be distinguished. Its annual grid-tariff costs decrease by €79.02 relative to Static, yet its total electricity costs increase by 0.95%. The increase in other electricity costs therefore outweighs the tariff saving, so a lower grid-tariff payment does not necessarily translate into a lower annual electricity bill.

ADT

Table 29 shows the change in cost exposure for the eight consumer profiles compared to the static case under the ADT mechanism.

Table 29: Change in consumer costs under the Adaptive Dynamic Tariff design compared with Static case

Profile	Δ tariff costs (€)	Δ total costs (%)
CP1	-179.96	-17.39
CP2	-378.39	-57.30
CP3	+15.52	+0.83
CP4	-29.19	-1.81
CP5	+166.29	+6.80
CP6	-182.91	-12.26
CP7	-32.14	-1.56
CP8	-98.07	-5.33

The tariff data of the ADT blocks can be found in Appendix D. Table 29 shows that ADT reduces both grid-tariff and total electricity costs for six of the eight profiles. CP2 experiences the largest tariff-cost reduction, at €378.39, followed by CP6 and CP1. CP3 and CP5 face increases of €15.52 and €166.29, respectively. CP5 again shows the largest increase. This is consistent with its combination of EV and heat-pump demand, without PV generation or battery storage to offset or shift grid imports. Neither EV nor heat-pump flexibility is activated in this profile, so its costs reflect the reference timing of both loads.

The distribution broadly resembles Full EmPower, although the magnitude of the changes differs. For example, CP8's total electricity costs decrease by 5.33% under ADT, compared with 9.58% under Full EmPower. Smoothing the hourly tariff into predefined periods therefore changes household-level outcomes without removing the redistribution associated with dynamic grid tariffs.

8.3 Tariff volatility

This subsection compares the variability of the underlying tariff signals using the coefficient of variation (CoV). This indicator expresses tariff variation relative to the mean tariff level. The mean, standard deviation, minimum, maximum, and coefficient of variation of the underlying tariff signals are reported in Table 59 in Appendix K.

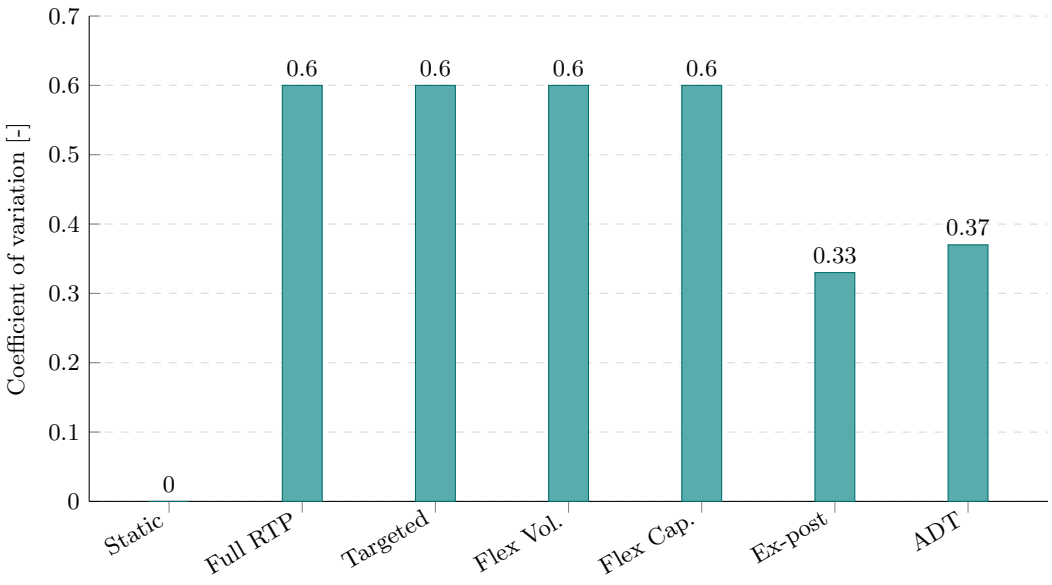

Figure 16: Tariff volatility of the evaluated grid-tariff mechanisms, expressed by the coefficient of variation (CoV). A higher CoV indicates greater tariff variation relative to the mean tariff level.

Figure 16 compares the relative variability of the underlying grid-tariff signals using the coefficient of variation (CoV). The Static tariff has no temporal variation. Full EmPower, Targeted EmPower, Flex Volumetric, and Flex Capacity share the same underlying dynamic tariff signal and therefore have an

identical CoV of approximately 0.60.

Identical tariff volatility does not imply identical consumer exposure. Targeted EmPower applies the dynamic component only to the targeted consumption, while the subscription mechanisms shield consumption within the subscribed volume or capacity from this component. Their CoV therefore describes the variability of the underlying tariff, rather than the variability of household bills or the share of consumption exposed to hourly tariff changes.

Ex-post Bonus has a lower CoV of approximately 0.33. However, its standard deviation remains equal to that of Full EmPower, at €0.0372/kWh. The lower CoV results from the higher mean tariff: approximately €0.1125/kWh, compared with €0.0625/kWh under Full EmPower. The same absolute fluctuations are consequently smaller relative to the mean. This difference should not be interpreted as a reduction in absolute tariff fluctuations caused by the ex-post rebate.

ADT reduces both relative and absolute tariff variation. Its CoV is approximately 0.37, while its standard deviation decreases to €0.0231/kWh. The maximum tariff also decreases from approximately €0.3776/kWh under Full EmPower to €0.1551/kWh under ADT. These results reflect the replacement of the directly congestion-responsive hourly tariff with predefined tariff blocks. ADT therefore produces a less variable tariff signal, whereas the subscription mechanisms retain the original signal while limiting exposure to it.

8.4 Cost recovery

This subsection compares aggregate annual grid-tariff revenues with those under the Static reference, indicating the extent to which each mechanism maintains reference revenues. The results are summarised in Appendix G.

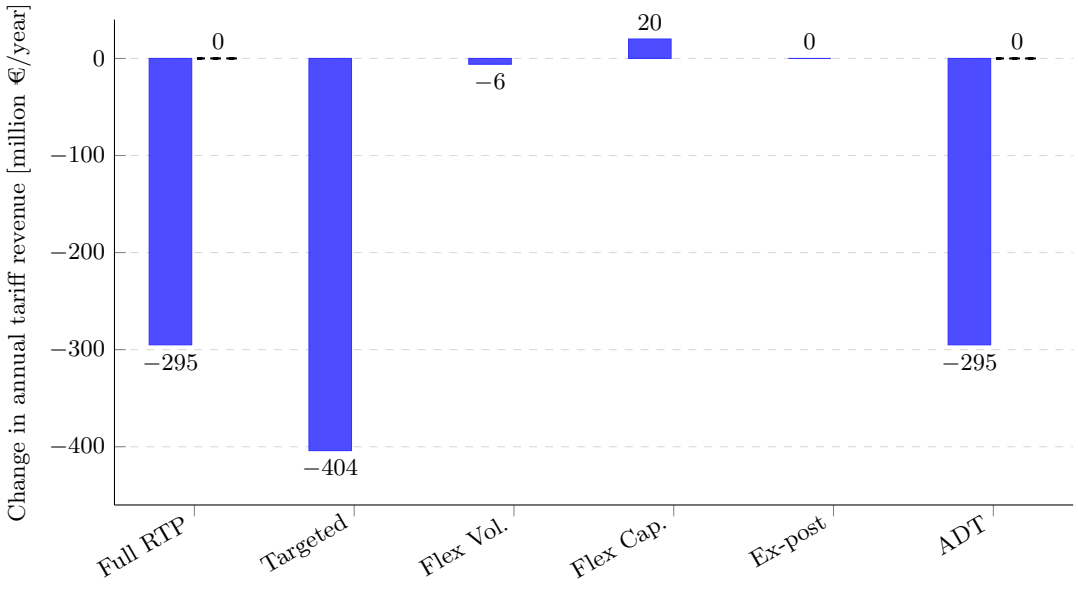

Figure 17: Cost recovery of the alternative grid-tariff mechanisms relative to the Static tariff. Negative values indicate lower annual tariff revenues than under the Static tariff, while positive values indicate higher annual revenues.

Figure 17 compares annual grid-tariff revenues with those under the Static tariff. Revenues are calculated using the assumed population shares of the household profiles and scaled to the total number of connections. Negative values indicate revenues below the static reference, while positive values indicate revenues above it. The indicator therefore measures recovery of reference tariff revenues rather than recovery of explicitly modelled network costs.

Full EmPower and Targeted EmPower generate approximately €295.2 million and €404.3 million less annual revenue than Static, respectively. Under the selected tariff calibration and simulated network conditions, the volumetric base charge and congestion-dependent charges do not reproduce the reference revenue. The limited occurrence of high-congestion periods contributes to this outcome. The demand sensitivity analysis further shows that higher demand increases tariff revenues, demonstrating their dependence on the assumed loading conditions. Targeted EmPower produces a larger shortfall because the dynamic component applies to a smaller share of consumption.
ADT produces a revenue shortfall of approximately €295.3 million, closely matching Full EmPower. Although the temporal distribution of tariff levels differs, translating the congestion-related signal into predefined tariff blocks does not restore aggregate reference revenues under the selected calibration.

The subscription mechanisms remain considerably closer to revenue neutrality. Flex Volumetric generates approximately €6.1 million less than Static, while Flex Capacity generates approximately €19.8 million more. These outcomes partly reflect the calibration of subscription fees with reference revenue recovery in mind. They should therefore be interpreted as outcomes of the selected subscription prices and model assumptions, rather than as an inherent guarantee of revenue neutrality.

Ex-post Bonus reproduces the aggregate static reference revenue by construction. The higher base tariff is combined with a uniform ex-post rebate that returns the resulting surplus to consumers. The zero revenue difference therefore follows from the settlement rule. As shown in the cost-exposure results, this aggregate neutrality does not imply unchanged costs for individual household profiles.

8.5 Congestion reflectiveness

This subsection assesses how closely the underlying tariff signals reflect hourly congestion intensity using the Pearson correlation coefficient. The results are summarised in Appendix G.

Table 30: Tariff reflectiveness of the evaluated grid-tariff mechanisms.

Mechanism	**Pearson** r
Static	–
Full RTP	1.00
Targeted RTP	1.00
Flex Vol.	1.00
Flex Cap.	1.00
Ex-post	1.00
ADT	0.62

Table 30 reports the Pearson correlation between the underlying grid-tariff signal and the congestion indicator. Full EmPower, Targeted EmPower, Flex Volumetric, Flex Capacity, and Ex-post Bonus all have a correlation of 1.00 under the simulated conditions. These mechanisms retain the same congestion-dependent temporal variation. The higher base tariff under Ex-post Bonus does not change this correlation, as adding a constant to the tariff leaves Pearson's correlation unchanged.

For Targeted EmPower and the subscription mechanisms, this result concerns the underlying tariff signal rather than the extent to which consumption is exposed to it. Targeting and subscription thresholds limit the application of the dynamic component without changing its relationship with the congestion indicator. An identical correlation therefore does not imply identical financial incentives across households or assets.

ADT has a lower correlation of approximately 0.62. Its predefined tariff blocks reflect expected congestion patterns rather than following each hourly change in congestion intensity. The positive correlation indicates that the tariff retains a relationship with congestion conditions, although the temporal correspondence is weaker than under Full EmPower. Together with the volatility results, this shows that the reduced tariff variation under ADT is accompanied by a less direct relationship with hourly congestion.

No correlation is reported for Static because its tariff does not vary over time, making Pearson's correlation undefined. Static provides no time-varying congestion signal. More generally, the correlation measures the correspondence between tariff levels and congestion conditions; it does not measure realised congestion reduction following consumer responses.

8.6 Economic incentives

This section presents the economic incentive results based on the data provided in Appendix H.

8.6.1 Flexibility benefits

Figure 19 presents the annual financial benefits of flexible operation for PV curtailment, EV smart charging, heat-pump flexibility, and battery operation. Benefits are calculated relative to the corresponding reference operation under the same tariff mechanism and include both grid-tariff and electricity-price effects. The endpoint represents the sum of the separately calculated asset-specific benefits, rather than the jointly achievable saving of a household operating all four assets. The detailed values are reported in Table 51.

The flexibility benefits presented below are calculated separately and are not incorporated into the reported cost-exposure results. These results use profiles without activated flexibility, except for CP8, which already includes optimised battery operation. The battery benefit for CP8 should therefore not be interpreted as an additional saving on its reported annual costs.

Figure 18 illustrates how to read the comparison: from left to right, the segments represent PV curtailment, EV smart charging, heat-pump flexibility, and battery operation. Each segment's length indicates the corresponding asset-specific benefit, while the endpoint marks their sum. This layout allows both the summed benefits and the relative contributions of individual assets to be compared across mechanisms. Segment lengths in the schematic are illustrative and not to scale. The same layout is applied in the following section containing the congestion reduction incentives.

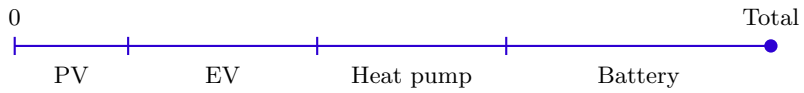

Figure 18: Schematic order of asset contributions. Segment lengths are illustrative and not to scale.

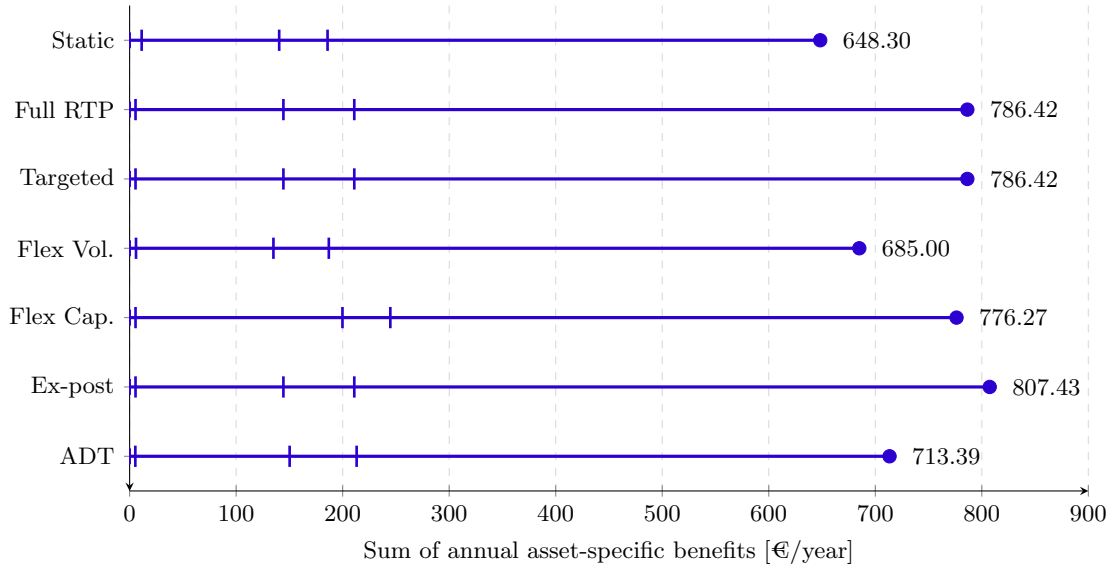

Figure 19: Sum of annual asset-specific flexibility benefits under the evaluated grid-tariff mechanisms. From left to right, the segments represent PV curtailment, EV smart charging, heat-pump flexibility, and battery operation. Vertical markers separate the contributions; dots indicate their sum. Benefits include both grid-tariff and electricity-price effects. The sum does not necessarily represent the jointly achievable benefit for a household operating all four assets.

The sum ranges from €648.30 under Static to €807.43 under Ex-post Bonus. Full EmPower and Targeted EmPower both yield €786.42, as targeting the dynamic tariff does not change the calculated benefits for the considered flexible assets. Flex Capacity produces €776.27, compared with €685.00 under Flex Volumetric and €713.39 under ADT. The positive benefits under Static demonstrate that flexibility also has financial value without a dynamic grid tariff: consumers can reduce electricity costs by responding to the electricity-price signal and avoiding unfavourable exports.

Battery operation provides the largest benefit under every mechanism, followed by EV smart charging, heat-pump flexibility, and PV curtailment. Annual battery benefits range from €462.49 under Static to €596.52 under Ex-post Bonus and consequently account for the largest share of the summed benefits. PV curtailment provides comparatively small benefits, ranging from €5.35 to €11.30. In the model, curtailment is restricted to surplus generation that would otherwise be exported at a negative marginal value, limiting the situations in which it produces savings.

Table 31: Economic incentives for flexibility under the EmPower Flex Capacity design

Flexibility measure	**Tariff benefit (€)**	**Total benefit (€)**
PV curtailment	-2.24	5.54
EV smart charging	67.72	194.27
Heat pump flexibility	0.27	44.93
Battery use	179.25	531.53

Table 32: Economic incentives for flexibility under the EmPower Flex Volumetric design

Flexibility measure	**Tariff benefit (€)**	**Total benefit (€)**
PV curtailment	-2.00	6.00
EV smart charging	0.00	129.00
Heat pump flexibility	7.00	52.00
Battery use	122.00	498.00

Tables 31 and 32 illustrate the differences between the two subscription mechanisms. EV smart charging provides a total annual benefit of €194.27 under Flex Capacity, compared with €129.00 under Flex Volumetric. The corresponding grid-tariff benefits are €67.72 and €0.00, respectively. This

is consistent with the capacity-based mechanism rewarding changes in charging schedules that reduce chargeable capacity exceedance. Battery operation also provides a larger total benefit under Flex Capacity, at €531.53 compared with €498.00 under Flex Volumetric.

The difference is reversed for heat-pump flexibility: its total benefit is €44.93 under Flex Capacity and €52.00 under Flex Volumetric. The associated grid-tariff benefits are €0.27 and €7.00, respectively. The capacity-based subscription therefore does not increase the financial value of flexibility uniformly across technologies. Its higher summed benefit primarily reflects the EV and battery outcomes.

To examine how the battery benefit arises under Flex Capacity, Table 33 compares CP7 without a battery with CP8 with optimised battery operation. Both profiles have identical underlying demand and PV profiles and the same subscribed capacity. During congestion periods, battery operation reduces capacity-exceedance energy from 301.83 to 148.33 kWh, a reduction of approximately 51%. Maximum household import during these periods decreases from 13.34 to 11.89 kW, while the number of exceedance hours remains unchanged at 53. The battery therefore reduces the magnitude of capacity exceedance without reducing its total duration. The annual maximum import, however, remains almost unchanged.

Table 33: Effect of optimised battery operation on capacity exceedance during congestion and annual grid-tariff savings under Flex Capacity. CP7 and CP8 have identical underlying demand and PV profiles and the same capacity subscription.

Indicator	CP7: no battery	CP8: battery
During congestion periods		
Exceedance duration [h]	53	53
Exceedance energy [kWh]	301.83	148.33
Maximum household import [kW]	13.34	11.89
Annual grid-tariff savings: CP7 minus CP8		*EUR/year*
Lower capacity-exceedance charges		38.35
Higher grid-tariff export remuneration		140.89
Total grid-tariff benefit		179.25

Annual savings include all hours. Component sums may differ from totals due to rounding. The full comparison is provided in Table 52 in Appendix H.

The financial breakdown shows that lower capacity-exceedance charges account for €38.35 of the annual grid-tariff benefit of €179.25. Approximately €140.89 instead comes from increased grid-tariff remuneration for electricity exports. The battery's tariff benefit thus reflects both reduced chargeable exceedance and changes in exports, with the export component providing the larger contribution. These results show how reduced capacity-exceedance charges and increased export remuneration contribute to the battery benefit under Flex Capacity. Explaining the difference with Flex Volumetric would require an equivalent breakdown for that mechanism. The full comparison of CP7 and CP8 under Flex Capacity is reported in Table 52 in Appendix H.

ADT also affects technologies differently. Relative to Full EmPower, the total battery benefit decreases from €575.51 to €500.27, while the EV benefit increases from €138.83 to €144.87. The lower summed benefit under ADT therefore does not imply lower benefits for every asset. These results highlight the importance of retaining the asset-specific outcomes alongside the aggregate comparison.

8.6.2 Congestion reduction incentives

The tariff-related flexibility benefit measures the financial incentive provided by the congestion-based tariff mechanism for the evaluated flexible operation. A higher benefit indicates greater grid-tariff savings from that operation, but does not directly quantify the resulting reduction in network congestion.

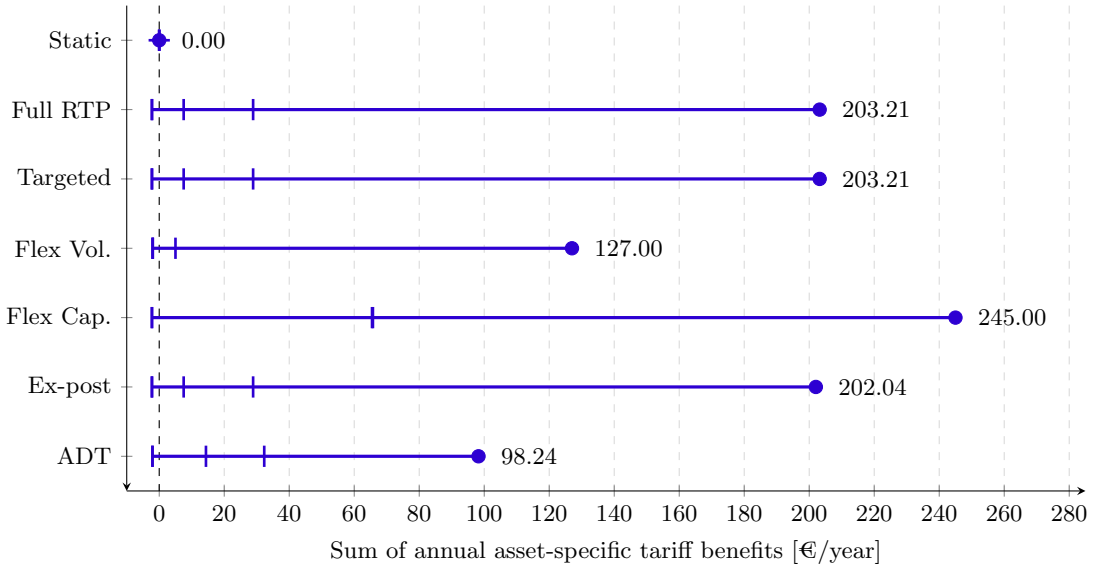

Figure 20: Cumulative annual grid-tariff benefits across the evaluated flexible assets. Vertical markers indicate the cumulative benefits after PV curtailment, EV smart charging, and heat-pump flexibility, respectively. Dots indicate the net sum after adding battery operation. Negative PV benefits are included in the cumulative values. Sums aggregate separately calculated asset-specific benefits and do not necessarily represent jointly achievable household savings or realised physical congestion reduction.

Figure 20 compares the summed tariff-related flexibility benefits across the evaluated assets, with the segments showing their individual contributions. Static provides no grid-tariff savings from flexible operation because its fixed annual charge is unaffected by changes in electricity use. Flex Capacity produces the highest sum, followed by Full EmPower, Targeted EmPower, and Ex-post Bonus. Flex Volumetric and ADT produce smaller summed benefits.

ADT has the same annual mean tariff as Full EmPower, but smaller differences between hourly tariff levels. Its predefined blocks reduce opportunities to obtain tariff savings by shifting electricity use between hours. This is consistent with the substantially lower battery-related tariff benefit under ADT. However, the effect differs between assets: the EV tariff benefit is higher under ADT than under Full EmPower.

The subscription mechanisms differ in how demand becomes exposed to the dynamic tariff. Flex Capacity charges import above the subscribed capacity in each hour, whereas Flex Volumetric applies dynamic charges after the monthly subscribed volume has been exceeded. Shifting EV charging can therefore reduce chargeable capacity exceedance even when total monthly consumption remains unchanged. In the evaluated case, EV smart charging produces a tariff benefit of €67.72 under Flex Capacity, compared with zero under Flex Volumetric. This difference does not extend uniformly to other assets: heat-pump flexibility provides a larger tariff benefit under Flex Volumetric, while the battery benefit also depends on changes in export remuneration.

8.6.3 Effective tariff burden

This subsection compares annual grid-tariff costs per imported kWh across consumer profiles, expressed as changes relative to the Static tariff. The annual import volumes used to calculate this indicator are reported in Table 58 in Appendix J. The figure uses consistent colours and markers to identify each consumer profile across mechanisms, enabling a direct comparison of the direction and magnitude of changes. This makes recurring profile-level patterns and differences between mechanisms easier to identify than in a large numerical table. The exact profile-level values are provided in Appendix H.

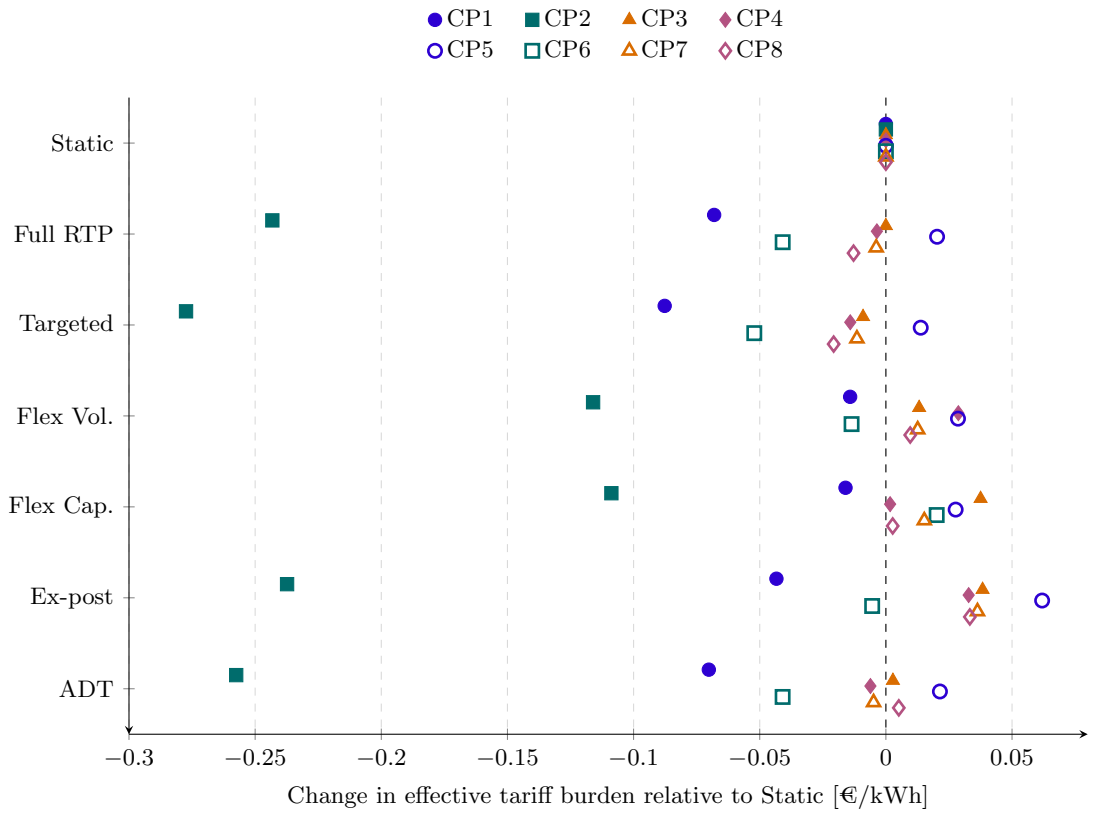

Figure 21: Change in effective grid-tariff burden relative to the Static tariff for each household profile. Effective tariff burden is calculated as annual grid-tariff costs divided by annual imported electricity under each mechanism. Negative values indicate a lower burden than under Static; positive values indicate a higher burden. Points are slightly offset vertically for readability; these offsets have no quantitative meaning.

Figure 21 shows the change in effective tariff burden for every consumer profile under each mechanism. Tariff burden means average price per kWh.

CP2 shows the largest reduction in effective tariff burden under all alternative mechanisms, followed by CP1, which also experiences a reduction under every alternative. This partly reflects their relatively high reference burden under the Static tariff, where a fixed annual charge is divided by a comparatively small imported electricity volume. CP5, which combines an EV and a heat pump, faces a higher effective tariff burden under every alternative. Under Static, its larger import volume spreads the fixed charge over more kWh, whereas the alternative mechanisms also differentiate charges according to the timing and characteristics of electricity use.

CP6 generally experiences a lower effective tariff burden, but this reverses under Flex Capacity, illustrating that PV ownership alone does not ensure a lower effective tariff burden. The remaining profiles cluster closer to zero, with the direction of the change depending on the mechanism.

The indicator depends on both annual grid-tariff costs and the imported electricity volume under each mechanism. For CP8, whose import volume changes between mechanisms, a reduction in annual grid-tariff costs can therefore coincide with a higher effective burden per imported kWh. These results should not be interpreted directly as changes in total annual electricity costs or as a complete assessment of asset investment incentives.

8.7 Price signal interaction

Figure 22 presents the share of hours in which the grid-tariff and electricity-price signals are aligned or conflicting.

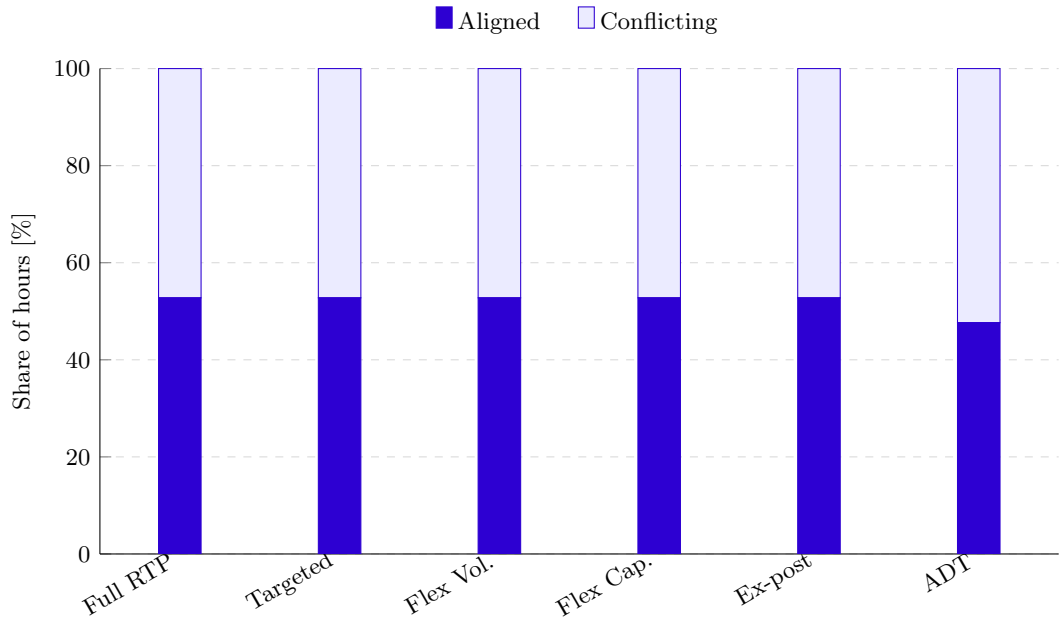

Figure 22: Interaction between the grid-tariff signal and the dynamic electricity-price signal. Aligned hours indicate that both signals provide an incentive in the same direction, while conflicting hours indicate opposing incentives.

Signals are classified as aligned when both hourly values are above their respective annual means or both are below them. They are classified as conflicting when one is above its mean and the other is below. This classification describes the relative direction of the signals rather than their absolute magnitude.

Full EmPower, Targeted EmPower, Flex Volumetric, Flex Capacity, and Ex-post Bonus show aligned signals during 52.77% of the hours and conflicting signals during 47.23%. These identical outcomes reflect their shared underlying hourly tariff pattern. The higher base tariff under Ex-post Bonus does not change the classification, because the tariff is compared with its own annual mean. Targeting and subscription thresholds likewise do not change the underlying signal, although they affect which consumption is financially exposed to it.

ADT shows aligned signals during 47.65% of the hours and conflicting signals during 52.35%. Its predefined tariff blocks therefore produce a slightly higher share of conflicting hours than the mechanisms retaining the original EmPower signal. Static is not included because it provides no time-varying grid-tariff signal.

The results indicate that relatively inexpensive electricity-market hours do not consistently coincide with relatively low grid tariffs. Flexible operation therefore depends on the combined financial effect of both signals. Neither alignment nor conflict is inherently preferable: a conflicting grid tariff may provide a local congestion-related incentive that is absent from the electricity price. Moreover, the reported shares weight every hour equally and do not measure the magnitude of the price differences, the affected electricity volume, or the resulting consumer response.

8.8 Results synthesis

The results show that retaining a congestion-reflective tariff signal does not imply identical financial exposure or flexibility incentives. Full EmPower, Targeted EmPower, the subscription mechanisms, and Ex-post Bonus retain the same correlation with the congestion indicator, while differing in how charges are applied and distributed. ADT changes the signal itself, reducing absolute tariff variation while weakening its correspondence with hourly congestion conditions.

Consumer cost exposure

Consumer cost outcomes must also be considered alongside tariff revenue recovery. Full EmPower, Targeted EmPower, and ADT reduce average household grid-tariff payments relative to Static under the simulated conditions, but also generate substantial aggregate revenue shortfalls. The calibrated subscription mechanisms remain closer to the reference revenue, while Ex-post Bonus restores it by construction. These aggregate outcomes nevertheless conceal substantial differences between household profiles: revenue neutrality does not imply unchanged individual costs, and shielding consumption from dynamic charges does not necessarily produce a lower annual bill.

Effective tariff burden

The effective tariff burden results show that CP1 and CP2 face lower grid-tariff costs per imported kWh under every alternative mechanism, while CP5 faces a higher burden. These differences partly reflect the Static tariff, where the same fixed annual charge is spread over different import volumes. CP5 nevertheless has flexibility options through its EV and heat pump, neither of which is operated flexibly in this comparison. Activating this flexibility could reduce its tariff burden, although the combined effect for CP5 has not been quantified. Since the indicator depends on both tariff costs and electricity imports, lower annual tariff payments do not necessarily imply a lower effective burden per kWh. The profile-specific results therefore provide an additional perspective on the distribution of tariff costs, without representing a complete assessment of asset investment incentives.

Flexibility results

The flexibility results further show that financial benefits depend on both the mechanism and the asset. Battery operation provides the largest total benefit under every mechanism. Flex Capacity produces the highest sum of tariff-related benefits across the evaluated assets, with greater EV and battery benefits than Flex Volumetric, but a smaller heat-pump benefit. The detailed battery comparison under Flex Capacity shows that battery operation reduces the magnitude of capacity exceedance during congestion without reducing the number of exceedance hours. However, most of its grid-tariff benefit comes from increased export remuneration rather than lower capacity-exceedance charges. Similarly, ADT reduces the summed flexibility benefit relative to Full EmPower while increasing the EV benefit. Aggregate comparisons therefore need to be interpreted alongside the individual asset outcomes and the components underlying their financial benefits.

Flexibility retains financial value under Static because consumers can respond to variations in electricity prices. Under the dynamic mechanisms, relatively low electricity prices do not always coincide with relatively low grid tariffs, so flexible operation responds to their combined financial effect. Total flexibility benefits therefore include electricity-price effects as well as grid-tariff effects. Moreover, these financial benefits do not establish realised congestion reduction, since network loading is not recalculated after flexibility activation.

Together, the results identify differences in household cost distribution, reference revenue recovery, tariff variation, and asset-specific incentives. Chapter 9 combines these findings with the qualitative criteria to assess the resulting design trade-offs and motivate the preferred mechanism.

9 Evaluation

This chapter evaluates the tariff designs introduced in Chapter 6 by combining the quantitative findings from Chapter 8 with the qualitative criteria defined in Chapter 5. It first outlines the evaluation approach, then examines the trade-offs between the quantitative criteria. The qualitative assessment subsequently considers implementation requirements, recurring burdens, clarity of purpose, actor roles, and non-discrimination. Finally, the integrated assessment identifies a preferred design direction and discusses the conditions and limitations associated with this choice.

9.1 Evaluation approach

The evaluation combines the quantitative model results presented in Chapter 8 with the qualitative assessment rules defined in Chapter 5. The purpose of the evaluation is not to aggregate all criteria into a single numerical ranking, but to make the performance differences and trade-offs between the mechanisms explicit.

To ensure a structured and consistent evaluation process, the assessment follows three consecutive steps.

First, the underlying evidence for each criterion is collected. For the quantitative criteria, this evidence consists of the numerical indicators calculated in Chapter 8 according to the formulas defined in Section 5.5.3. For the qualitative criteria, the evidence consists of the observable mechanism characteristics defined in Section 5.5.4.
Second, these observations are translated into criterion-level assessments using predefined decision rules. Quantitative criteria are compared directly using their numerical indicator values. Qualitative characteristics are coded as present or absent and subsequently translated into an ordinal assessment according to the scoring rules defined in Chapter 5.
Third, the resulting criterion-level outcomes are compared across mechanisms. No weights are assigned to the criteria and no overall numerical score is calculated. The evaluation therefore identifies trade-offs rather than determining a mathematically optimal design.

As background information, the evaluation tables report the underlying quantitative values or qualitative assessment counts from which the final interpretation is derived. The detailed qualitative coding matrices are provided in Appendix I.

9.2 Trade-offs between quantitative criteria

The quantitative results reveal several trade-offs between consumer cost exposure, reference revenue recovery, tariff stability, and financial incentives for flexibility. These criteria cannot be interpreted independently. Lower household payments may coincide with lower DSO revenues, while shielding consumption from dynamic charges can change the incentives available to flexible assets. Appendix F reports the profile-level consumer costs, Appendix H provides the asset-specific flexibility benefits and effective tariff-burden results, and Appendix G summarises the quantitative indicators presented in Chapter 8. The following assessment considers the relationships between these results under the model assumptions and tariff calibrations used in this study.

Consumer costs and reference revenue recovery

Full EmPower, Targeted EmPower, and ADT reduce average household grid-tariff payments relative to Static, but also generate substantial aggregate revenue shortfalls. Lower payments therefore do not, by themselves, demonstrate that these mechanisms provide a financially sustainable reduction in consumer costs. If the static reference revenue must be maintained, additional charges or a different calibration would be required, changing the household outcomes reported in Chapter 8. Targeted EmPower illustrates this relationship particularly clearly: excluding non-targeted consumption from the dynamic component lowers household payments further, but increases the revenue shortfall.

The subscription mechanisms and Ex-post Bonus address reference revenue recovery more directly. Their outcomes nevertheless depend on the selected subscription prices and settlement rules. Near-neutral revenues under the subscription mechanisms partly follow from calibration, while neutrality

under Ex-post Bonus is imposed by construction. These results demonstrate how reference revenues can be recovered within the proposed designs, rather than establishing that the mechanisms will remain revenue-neutral under different demand patterns or consumer responses.

Revenue recovery also needs to be distinguished from the distribution of costs. Ex-post Bonus restores aggregate reference revenues while producing the widest range of household tariff-cost changes. Similarly, the subscription mechanisms shield part of consumption from dynamic charges but increase annual payments for several profiles. Protecting consumption from hourly price variation and limiting the annual financial burden are therefore separate design objectives.

The revenue indicator does not capture the full economic position of the DSO. Potential benefits from avoided congestion, additional connections, or postponed reinforcement are outside the model. Consequently, a revenue shortfall cannot be interpreted as an equivalent loss of overall economic value, but neither can unquantified network benefits be assumed to compensate for it.

Consumer protection and flexibility incentives

The subscription designs show that limiting exposure to a dynamic tariff does not necessarily remove its flexibility incentives. Both retain the underlying congestion-related signal while determining which consumption is exposed to it. Their different outcomes demonstrate that the subscription boundary matters: a monthly volume allowance and a capacity threshold do not create the same opportunities for reducing charges.

Flex Capacity produces greater EV and battery tariff benefits than Flex Volumetric, but a smaller heat-pump benefit. Its higher sum of tariff-related benefits therefore does not represent a uniform improvement across technologies. The capacity threshold appears particularly relevant for the modelled EV charging profile, whereas the heat-pump results show that some flexible loads obtain little additional tariff benefit. The relative attractiveness of the two designs consequently depends partly on the assets and demand characteristics of the households to which they are applied.

Financial flexibility opportunities must also be considered alongside the costs faced by households before they respond. A mechanism may impose higher charges on a profile while offering opportunities to reduce those charges through flexible operation. Such opportunities are not equivalent to guaranteed protection, particularly where consumers have limited controllable demand. The effective tariff burden results reinforce this distributional concern: CP1 and CP2 face lower charges per imported kWh under all alternatives, whereas CP5 faces higher charges. These differences indicate that no mechanism improves the tariff treatment of every household configuration.

Consumer savings and congestion-related incentives

The mechanism with the largest total flexibility benefit is not necessarily the mechanism with the largest grid-tariff benefit. Ex-post Bonus produces the highest sum of total asset-specific benefits, whereas Flex Capacity produces the highest sum of tariff-related benefits. Static also provides substantial total flexibility benefits despite having no time-varying grid-tariff incentive. These outcomes show that consumer savings depend on the combined electricity-price and grid-tariff effects.

The price-signal interaction results help explain why these objectives can diverge. Relatively inexpensive electricity-market hours do not always coincide with relatively low grid tariffs. A consumer minimising combined costs may therefore accept higher grid-tariff costs to obtain larger electricity-price savings. A higher share of aligned hours is not inherently preferable, since an opposing grid-tariff signal may communicate local congestion conditions that are absent from the electricity price.

Tariff-related benefits provide evidence of financial incentives, but do not establish realised congestion reduction. Network loading is not recalculated after flexibility activation, and the sum across separately assessed assets is not a jointly optimised household or system outcome. The quantitative comparison therefore supports conclusions about the distribution and strength of modelled financial incentives,

rather than a definitive ranking of physical congestion-management performance.

Tariff stability and congestion reflectiveness

ADT and the subscription mechanisms pursue different forms of protection. ADT reduces the variability of the tariff signal itself, while subscriptions retain the original signal and limit its application. The identical volatility and correlation indicators of the EmPower-based subscription designs therefore do not imply identical household exposure. Conversely, a less variable tariff does not automatically imply a lower annual bill.

ADT provides the clearest trade-off between absolute tariff stability and correspondence with hourly congestion. Its predefined blocks reduce tariff fluctuations, but its lower correlation indicates that individual congestion events are reflected less directly. The lower battery-related tariff benefit is consistent with fewer opportunities to exploit short-term tariff differences. However, the EV benefit exceeds that under Full EmPower, so the effect of smoothing cannot be generalised to every asset.

Ex-post Bonus should be assessed differently. Its lower coefficient of variation results from a higher mean tariff rather than smaller absolute fluctuations. It therefore combines revenue redistribution with a retained hourly congestion signal, rather than providing the same form of tariff stabilisation as ADT. This distinction matters when evaluating whether a design addresses fluctuating prices, exposure to those prices, or the final annual payment.

These trade-offs identify different conditions under which the mechanisms may be attractive. The subscription designs combine reference revenue recovery with selective dynamic exposure, ADT reduces absolute tariff variation, and Ex-post Bonus restores aggregate revenues while retaining hourly tariff variation. Whether these characteristics provide an appropriate overall balance also depends on implementation requirements and the priorities assigned to consumer protection and congestion-related incentives. The qualitative assessment and integrated design evaluation address these considerations in the following sections.

9.3 Qualitative assessment and implementation implications

The qualitative criteria are evaluated using the predefined assessment rules introduced in Section 5.5.4. For each mechanism, the observable characteristics are assessed individually and translated into a Good, Moderate, or Poor performance score according to the corresponding decision rule. The detailed coding matrices and justification of the individual observations are provided in Appendix I. This section therefore focuses on the resulting criterion-level scores and the main differences between the evaluated mechanisms.

Table 34: Qualitative evaluation of the market mechanisms

Criterion	Static	Full RTP	Targeted	Flex Vol.	Flex Cap.	Ex-post	ADT
Simplicity of implementation	Good	Moderate	Poor	Poor	Poor	Moderate	Moderate
Limited additional burdens	Good	Moderate	Poor	Moderate	Moderate	Moderate	Moderate
Clear purpose	Poor	Good	Good	Moderate	Good	Moderate	Good
Delineation of actor roles	Good	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Non-discrimination	Good	Moderate	Poor	Moderate	Moderate	Moderate	Moderate

Table 34 summarises the criterion-level assessments. The main differences between mechanisms are discussed below.

Simplicity of implementation

The static tariff performs best on simplicity of implementation because it represents the existing tariff structure and therefore introduces no additional implementation requirements. Full EmPower and

ADT receive a Moderate assessment because they require additional billing logic and information exchange, but do not require separate subscription or asset-management systems. Targeted EmPower performs poorly because flexible assets must be identified, registered, and measured separately.

The two subscription mechanisms also receive a Poor assessment. In addition to new billing and subscription administration, both require a new monitoring and communication system to determine when the subscribed volume or capacity is exceeded and to communicate the resulting tariff exposure to consumers or automated energy-management systems. The Ex-post Bonus remains Moderate, but also requires additional technical infrastructure to calculate, execute, and communicate the financial correction after the settlement period.

Limited additional burdens

A similar pattern is observed for additional recurring burdens. The static tariff does not introduce new recurring activities and therefore performs best. Full EmPower, ADT, the subscription mechanisms, and the Ex-post Bonus introduce additional recurring activities related to tariff processing, monitoring, settlement, or administration and therefore receive a Moderate assessment. Targeted EmPower performs least favourably because asset registration, measurement, billing, and coordination must be maintained continuously after implementation.

Clear purpose

The dynamic mechanisms generally perform favourably on clear purpose because their tariff rules establish an identifiable relationship between congestion conditions, consumer behaviour, and tariff costs. Full EmPower and Targeted EmPower provide a clear incentive to shift flexible demand away from high-tariff congestion periods. Flex Capacity directly links dynamic tariff exposure to household import exceeding the subscribed capacity, providing an identifiable behavioural target. ADT also provides a clear behavioural signal through predefined high- and low-tariff periods. Flex Volumetric performs moderately because monthly electricity volume is less directly related to congestion-reducing behaviour. The Ex-post Bonus receives a Moderate assessment because the additional redistribution step makes the relationship between hourly tariff charges and the final annual payment less straightforward to communicate. The static tariff performs poorly because it does not provide a congestion-related behavioural signal.

Delineation of actor roles

The static tariff performs best because it operates within the existing allocation of responsibilities. All dynamic mechanisms introduce additional responsibilities and require more intensive coordination between existing actors, particularly between the DSO and suppliers. Full EmPower and ADT mainly require additional coordination for tariff determination, communication, and billing. Targeted EmPower, the subscription mechanisms, and the Ex-post Bonus additionally require further delineation of responsibilities related to asset registration, subscription administration, or ex-post settlement. These mechanisms therefore create greater institutional coordination requirements than the static tariff, although no fundamentally new market actor is required.

Non-discrimination

The static tariff performs best on non-discrimination because comparable consumers are subject to the same tariff conditions regardless of location, asset type, or purpose of electricity use. All EmPower-based mechanisms include locational differentiation because tariff levels depend on local congestion conditions. As a result, otherwise comparable electricity use may face different tariff treatment depending on the connection location, resulting in a Moderate assessment for most dynamic mechanisms. Targeted EmPower performs least favourably because, in addition to locational differentiation, tariff treatment also depends on the type of electricity use: registered flexible assets are exposed

to the dynamic tariff while other household consumption is not. ADT similarly contains locational differentiation through locally determined tariff periods and therefore also receives a Moderate assessment.

Qualitative evaluation synthesis
The qualitative evaluation shows that the mechanisms primarily differ in the amount of organisational and technical complexity they introduce compared with the existing tariff structure. The static tariff performs favourably on implementation simplicity, additional burdens, role delineation, and non-discrimination, but provides no clear congestion-related purpose. Full EmPower and ADT retain relatively clear tariff logic and do not require fundamentally new consumer-level tariff infrastructure, although both require additional coordination and processing of dynamic tariff information.

Targeted EmPower combines Poor assessments for implementation simplicity, recurring burdens, and non-discrimination, reflecting the additional requirements associated with asset-specific tariff treatment. The subscription mechanisms also involve a substantial implementation challenge. They receive a Moderate assessment for recurring burdens under the specified scoring rules, while requiring new subscription, monitoring, and communication systems to determine and communicate dynamic tariff exposure. Flex Capacity nevertheless retains a clear congestion-related purpose. The Ex-post Bonus avoids subscription administration but introduces an additional settlement and transaction process, making the relationship between hourly tariff charges and the final annual payment less straightforward to communicate.

9.4 Integrated assessment and preferred design

The evaluation does not identify a mechanism that performs best across all criteria. Since no numerical weights are assigned, the preferred design represents a reasoned judgement based on the research objective rather than a mathematically optimal solution. The selection prioritises retaining congestion-related financial incentives while limiting the share of household demand exposed to dynamic charges and maintaining revenues close to the static reference. Implementation requirements and differences between household outcomes are considered alongside these objectives.

Preferred design: EmPower Flex Capacity

On this basis, EmPower Flex Capacity is selected as the preferred design direction within the assumptions of this study. Its capacity subscription shields demand within the subscribed capacity while retaining dynamic charges for exceedance. Because these dynamic charges increase when congestion occurs, demand reduction during congestion periods is financially incentivized. Under the selected calibration, it combines revenues close to the static reference with the highest sum of tariff-related flexibility benefits across the evaluated assets. Compared with Flex Volumetric, it provides greater EV and battery benefits and links dynamic exposure to capacity exceedance rather than cumulative monthly consumption. Its Good assessment for clear purpose also supports the communication of this relationship between demand, the subscription threshold, and tariff exposure.

This preference does not imply that Flex Capacity provides the strongest incentive or the lowest costs for every household. Its heat-pump tariff benefit is smaller than under Flex Volumetric, and several profiles face higher annual charges than under Static. Shielding part of demand from dynamic charges therefore does not guarantee a lower annual bill. Moreover, the near-neutral revenue outcome in the base case depends partly on subscription-price calibration. Across the consumer-composition scenarios in the sensitivity analysis, annual tariff revenues range from approximately €70 million below to €111 million above the Static reference. Flex Capacity remains closer to the reference revenue than Full EmPower in these scenarios, but this does not imply revenue neutrality across different consumer populations. The summed tariff benefits also do not establish realised physical congestion reduction. Further assessment of subscription levels, household distributional effects, and network responses is therefore needed before implementation.

Implementation challenges

The quantitative advantages also come with substantial implementation requirements. Flex Capacity receives a Poor assessment for simplicity of implementation because subscription administration, monitoring, and communication must be established to determine and explain dynamic exposure. Its Moderate assessments for recurring burdens and actor-role delineation indicate that continuing administrative and coordination requirements also remain. Selecting this design therefore means accepting greater implementation complexity in pursuit of selective consumer protection and asset-specific flexibility incentives; it does not mean that this complexity has been shown to be outweighed by quantified network benefits.

Potential role of aggregators

The actor analysis in Chapter 4 identifies aggregators as potential intermediaries between consumers and flexibility markets. Building on this role, aggregators could reduce the complexity experienced by consumers under Flex Capacity by translating tariff signals and subscription limits into automated operating decisions. Coordinating flexible assets in line with household preferences could reduce the need for consumers to monitor hourly tariffs or manage capacity exceedance themselves. This would shift part of the operational complexity towards service providers rather than remove the underlying implementation requirements. The extent to which these services improve accessibility would depend on their costs, available control systems, and the allocation of responsibilities. Their contribution has not been quantified in the model.

Alternative designs under different priorities

The alternatives remain relevant when different priorities are emphasised. Flex Volumetric offers a different distribution of flexibility benefits, including a larger heat-pump benefit, but weaker EV and battery tariff incentives in the model. Ex-post Bonus restores reference revenues while retaining the hourly congestion signal and receives a Moderate implementation assessment. However, its wide range of household cost changes makes it less aligned with a preference for shielding part of household consumption from dynamic exposure. These comparisons support Flex Capacity as the preferred direction under the stated priorities, rather than as a universally superior mechanism.

ADT as a potential intermediate step

ADT may offer a more accessible initial application where tariff predictability and implementation simplicity receive greater priority. It reduces absolute tariff variation and receives a Moderate implementation assessment, while preserving a positive relationship with congestion conditions. However, its current calibration leaves a substantial reference revenue shortfall, and its lower congestion reflectiveness and battery-related tariff benefit limit its ability to reproduce the incentives of the more dynamic designs. Any use of ADT as an intermediate step would therefore require reconsideration of revenue recovery and an assessment of whether its systems and processes support a later transition to capacity subscriptions. Such a transition is a possible implementation strategy, rather than an outcome tested by the model.

Within these boundaries, Flex Capacity provides the strongest basis for further design development given the combination of selective dynamic exposure, reference revenue recovery, and EV and battery flexibility incentives. The next stage should test whether these advantages persist under alternative network conditions, household compositions, subscription settings, and behavioural responses, and whether the associated implementation requirements are acceptable to the actors involved.

10 Discussion

This chapter discusses the scope and limitations of the findings and their implications for further research. It first examines how the input data, modelling assumptions, and evaluation approach affect the interpretation and generalisability of the results. It then outlines directions for future research to assess the mechanisms under a wider range of conditions and investigate their practical implementation.

10.1 Limitations

The findings of this research should be interpreted in light of several limitations related to the input data, modelling approach, representation of consumer behaviour, mechanism calibration, and evaluation method. These limitations do not prevent comparison between the tariff designs, since the same modelling assumptions are applied consistently across the alternatives, but they do affect the extent to which the numerical outcomes can be generalised to other network areas or future conditions.

Network data and congestion conditions

A first limitation concerns the representation of grid congestion. The evaluation is based on the loading conditions of a single medium-voltage substation and therefore represents one specific network context. Moreover, a complete measured annual loading profile was not available during the modelling phase, requiring the use of a synthetic but realistic annual profile. The simulated network mainly experiences consumption-driven congestion and contains limited injection-driven congestion. Consequently, the relative performance of the tariff designs may differ in areas with other load patterns, higher PV penetration, more severe congestion, or different transformer characteristics.

This limitation directly affects the generalisability of the quantitative results. Under the simulated congestion conditions, severe congestion and the corresponding high tariffs occur during a limited part of the year. This contributes to relatively low tariff costs for several consumer profiles under Full EmPower, but also to the substantial revenue shortfall observed for the DSO. In a network with more frequent or more severe congestion, consumer cost exposure and tariff revenues would likely increase, and exposure-limiting mechanisms such as Flex Capacity and Flex Volumetric could become relatively more valuable. Conversely, under milder congestion conditions, the financial benefits of such protection mechanisms may be smaller. The absolute financial outcomes and the relative attractiveness of the mechanisms should therefore be interpreted as conditional on the simulated network conditions rather than as universally applicable values.

A related limitation is the uncertainty surrounding the future development of grid congestion. Electrification and increasing peak demand may intensify congestion, while grid reinforcement, energy sharing, local coordination, energy hubs, or other flexibility mechanisms may reduce local network scarcity. The long-term relevance of the proposed mechanisms is therefore dependent on how congestion develops in practice. This means that the conclusion that Flex Capacity provides the most promising long-term balance should be interpreted as conditional on a future system in which local congestion remains sufficiently frequent and severe for dynamic congestion pricing to create meaningful incentives.
The sensitivity analysis in section 7.7.4 confirms this dependence: increasing demand leads to more frequent congestion, higher tariff levels, greater tariff volatility, and substantially higher DSO tariff revenues, while lower demand has the opposite effect. This demonstrates that the quantitative performance of the mechanisms is context-dependent and that the base-case results should not be interpreted as fixed outcomes for other network areas or future demand conditions.

In addition, network loading is treated as an exogenous input and the model does not perform physical power-flow calculations. Consumer flexibility therefore does not feed back into transformer loading or subsequently alter tariff levels. The model can identify whether flexible behaviour is financially encouraged in a congestion-supporting direction, but it cannot determine the realised aggregate reduction in congestion when many households respond simultaneously. As a result, the congestion-related flexibility benefit should be interpreted as an indicator of congestion-reduction potential rather than evidence of actual physical congestion relief. This also means that the preferred design is selected based on the strength and balance of incentives rather than on demonstrated network-level congestion

reduction.

Consumer profiles and behavioural response

A second limitation concerns the representation of consumers and their behavioural response. The model uses eight consumer archetypes to represent households with different combinations of base demand, PV, EVs, heat pumps, and battery storage. These profiles provide a structured way to compare the effects of the tariff mechanisms, but individual households can differ substantially in electricity demand, asset characteristics, occupancy patterns, and available flexibility. In addition, the assumed population distribution of the archetypes is derived from available data on the presence of household energy assets and therefore represents a scenario rather than an observed distribution of complete household configurations. This assumption mainly affects aggregate outcomes such as DSO cost recovery, which is sensitive to the relative prevalence of the different profiles, as shown in Section 7.7.4. Cost-recovery results should therefore primarily be interpreted as comparative outcomes between mechanisms rather than as exact predictions of future DSO revenues. Profile-level outcomes are less directly affected by this population-distribution assumption. The asset-ownership indicator is also limited to differences in grid-tariff costs per imported kWh. It does not compare the full economic performance of technologies with their conventional alternatives, such as an EV with a petrol vehicle or a heat pump with gas heating. The results therefore indicate a tariff-based incentive for asset ownership rather than a complete investment or total-cost-of-ownership assessment.

Consumer flexibility is represented using technical and behavioural assumptions regarding the share of EV and heat-pump demand that can be shifted, PV curtailment, and battery optimisation. These assumptions represent plausible flexibility patterns, but realised household response may differ. Automated energy-management systems could enable consumers to respond more consistently to tariff signals, whereas households without automation, with stronger comfort constraints, or with limited willingness to adapt may provide less flexibility than assumed. The resulting flexibility benefits should therefore be interpreted as an indication of the economic potential of available flexibility rather than as a prediction of realised consumer behaviour. Different behavioural assumptions would affect the magnitude of these benefits and therefore the estimated strength of the congestion-related incentive.

A further limitation concerns the subscription mechanisms. Subscription levels are assigned to consumer profiles based on their demand characteristics using the procedure described in Appendix E, rather than being selected endogenously by consumers within the model. The model therefore evaluates the consequences of the proposed subscription structure once a subscription has been assigned, but does not determine which subscription consumers would actually choose, whether they would strategically select a lower or higher tier, or whether they would adopt the mechanism at all. Consequently, the results provide insight into the performance potential of the subscription designs, but not into actual subscription-choice behaviour or participation rates.

Tariff design and calibration

A third limitation concerns the calibration of the tariff mechanisms. Several tariff parameters are based on the current EmPower project and on assumptions required to operationalise the conceptual designs. In particular, the subscription fees for Flex Volumetric and Flex Capacity were calibrated to provide approximately sufficient DSO cost recovery under the assumed network conditions and population distribution. These values should therefore be interpreted as reference values rather than optimal or directly implementable real-world tariffs. Their purpose is to demonstrate the capability of the proposed designs and compare the trade-offs they create under consistent conditions. Actual tariff levels would require further calibration based on network conditions, regulation, consumer participation, and implementation choices.

This parameter dependence affects the quantitative outcomes. Different tariff or subscription levels would change consumer cost exposure, DSO revenues, and flexibility incentives. The favourable cost-recovery performance of the subscription mechanisms is also partly related to their calibration, while the Ex-post Bonus is explicitly designed to restore aggregate reference revenues. Cost recovery should therefore be interpreted mainly as part of the mechanism comparison rather than as an independent prediction of future tariff revenues.

The Adaptive Dynamic Tariff also represents only one possible implementation of the broader ADT principle. In this research, tariff blocks are updated monthly based on expected congestion patterns, while alternative designs could use daily, weekly, or seasonal periods. Shorter update periods could increase congestion reflectiveness, whereas longer periods could improve stability and predictability. The ADT results therefore apply to the specific configuration evaluated here rather than to all possible adaptive tariff designs.

Overall, the mechanisms should be interpreted as design directions rather than fully calibrated tariff products. Their parameters would require further empirical testing, but the evaluated configurations provide useful reference cases for understanding how tariff structure, exposure limitation, and temporal resolution affect the main performance trade-offs.

Information, market interaction, and institutional scope
A fourth limitation concerns the interaction with the wider electricity market. The research identifies the roles and requirements of suppliers, BRPs, CSPs, and aggregators, but does not model their exact operational processes, such as portfolio management, imbalance settlement, flexibility activation, or inter-actor coordination. These aspects are therefore assessed qualitatively rather than through detailed simulation. The proposed mechanisms consequently provide a possible market structure, but further actor-specific analysis is required to determine how responsibilities, processes, and financial risks should be implemented in practice. This also means that the preferred design should be interpreted as institutionally promising rather than as a fully validated operational market arrangement.

Tariffs are furthermore evaluated using known network conditions. In practice, longer communication horizons require forecasts of future congestion, while forecast errors or failures in communication and control systems may reduce tariff accuracy or prevent the intended response. These reliability issues were also identified as important by interviewed market parties, but their detailed treatment requires additional technical and contractual assumptions outside the scope of this research. The mechanisms should therefore be interpreted as reference designs whose information and fallback procedures require further development before implementation.

Finally, the electricity market and its regulatory structure are developing rapidly, particularly through changing roles for aggregators and flexibility providers. Future role allocation may therefore differ from the structure assumed in this study. Nevertheless, the proposed mechanisms provide a reference framework that can be adapted as market roles evolve and can be used to assess which design changes are required under future institutional arrangements.

Interviews and evaluation method
A final limitation concerns the stakeholder interviews and evaluation method. Ten market organisations covering the relevant actor roles were interviewed, supplemented by consumer interviews. Although this provides broad actor coverage, other organisations or consumers could identify additional concerns, objectives, or implementation requirements. The combination of literature and interviews nevertheless suggests that the main stakes and trade-offs have been captured. Additional concerns would therefore be more likely to extend the evaluation framework than to invalidate the design structure developed in this research. The mechanisms could then be reassessed or adjusted to address these additional requirements.

The qualitative evaluation also depends on predefined assessment rules and researcher interpretation. No explicit weights were assigned to the criteria, and no aggregate score was calculated. The results should therefore primarily be interpreted comparatively, as showing the relative strengths, weaknesses, and trade-offs between mechanisms rather than producing an exact or universally optimal ranking. Consequently, the conclusion that Flex Capacity provides the most promising balance reflects the evaluation framework and assumptions applied in this study, while alternative stakeholder priorities or criterion weights could lead to a different preferred design. The comparative results remain useful under these alternative viewpoints, as stakeholders can interpret the mechanisms according to their own priorities and use the identified trade-offs as a basis for selecting or adapting a suitable design.

10.2 Directions for future research

The limitations and findings of this research provide several directions for further research. In particular, future work should further validate and refine Flex Capacity as the most promising long-term design direction and ADT as a potential transitional mechanism.

Evaluation under alternative network and congestion scenarios

A first priority is to evaluate the mechanisms under a wider range of network conditions. The current results are based on one network-loading profile with mainly consumption-driven congestion. Future research should therefore compare low-, medium-, and high-congestion scenarios, as well as areas with stronger injection congestion, different transformer characteristics, and different levels of PV penetration. This would show how sensitive consumer exposure, congestion incentives, and cost recovery are to the local network context and under which conditions subscription-based mechanisms become most valuable.

Representative consumer data and future population changes

Future research should assess the tariff mechanisms using more accurate data on the composition of the consumer population, for example within Stedin's service area. Information on household electricity demand, ownership of PV systems, EVs, heat pumps, and batteries, and the combinations of these assets would allow more representative weighting of consumer profiles. Where available, differences between local network areas should also be considered. This would strengthen the assessment of aggregate tariff revenues and the distribution of costs across households.

The analysis should also examine how these outcomes evolve as electrification and asset ownership change. Scenarios for future consumer populations could test whether subscription settings continue to provide adequate revenue recovery and how the distribution of costs and flexibility benefits develops over time. This would help identify whether, and how frequently, subscription levels and prices require recalibration.

System-level modelling of consumer response

Future models should allow the simultaneous response of a larger population of households to feed back into network loading and tariff formation. Combining the current market-based model with a physical network or power-flow model would make it possible to quantify realised congestion reduction, peak shifting, rebound effects, and the possible creation of new collective peaks. This would extend the current congestion-reduction indicator from an economic incentive measure towards an assessment of actual network relief.

Further calibration of Flex Capacity and ADT

The parameters of the proposed mechanisms should be further calibrated using empirical network and consumer data. For Flex Capacity, future research should investigate alternative subscription levels, fees, and settlement periods, while modelling subscription choice endogenously rather than assigning tiers based on demand profiles. For ADT, alternative update frequencies such as daily, weekly, or seasonal tariff blocks could be compared with the monthly configuration used in this research. This would provide further insight into the trade-off between stability, reflectiveness, consumer protection, and DSO revenue recovery.

Consumer behaviour, adoption, and automation

The current flexibility assumptions represent technically plausible response potential rather than observed household behaviour. Future behavioural and experimental research should therefore investigate how consumers actually respond to congestion-related tariffs, how they select capacity subscriptions,

and how complexity affects participation and acceptance. Field experiments could compare manual response with automated optimisation through HEMS, aggregators, or CSPs and determine to what extent the flexibility benefits identified in the model can be realised in practice. In addition, future research could extend the asset-ownership indicator into a full financial comparison between flexible electric technologies and their conventional alternatives. For example, the total cost of ownership of an EV could be compared with that of a petrol vehicle, and the cost of heat-pump operation with gas-based heating. Such an analysis could include investment costs, maintenance, fuel or gas costs, subsidies, electricity prices, grid tariffs, and expected asset lifetime. This would show whether the tariff-based incentives identified in this research are sufficiently large to materially influence technology adoption.

Tariff forecasting and communication reliability

Future research should also investigate the effect of forecast uncertainty and communication reliability. Congestion forecasts could be used to compare alternative publication horizons, such as day-ahead, three-day-ahead, or seven-day-ahead tariffs, and assess their effects on reflectiveness, flexibility, and BRP uncertainty. In addition, fallback procedures for forecast errors, communication failures, and unsuccessful flexibility activation should be developed, as these practical reliability issues were identified as important by market actors.

Market coordination and practical implementation

Further research should specify how the proposed mechanisms would operate within the wider electricity-market architecture. This includes detailed processes for suppliers, BRPs, CSPs, aggregators, and DSOs, the interaction with wholesale and balancing signals, and the allocation of responsibilities and financial risks. The technical and organisational implementation costs should also be quantified. Pilot testing of Flex Capacity and ADT could subsequently provide empirical evidence on billing, consumer acceptance, actor coordination, and practical congestion response.

Evaluation under alternative stakeholder priorities

Finally, future research could extend the evaluation framework by incorporating stakeholder-specific priorities or criterion weights. The current study deliberately avoids an aggregate weighted ranking, meaning that the preferred design reflects the balance identified within the applied framework. Eliciting weights from different actor groups would make it possible to test whether Flex Capacity remains preferred under alternative viewpoints and to identify which design modifications are required when particular stakeholder objectives receive greater importance.

11 Conclusion

This research investigated how a grid-tariff mechanism can provide effective incentives for congestion reduction through dynamic grid tariffs, while mitigating the associated risks. A design-oriented research approach was used in which actor requirements were first identified and translated into evaluation criteria. These criteria subsequently guided the construction, modelling, and evaluation of alternative tariff mechanisms. The conclusions are presented according to the four research subquestions, followed by the answer to the main research question.

11.1 Research questions

11.1.1 Subquestion 1

Which actors are impacted by dynamic grid tariffs, and what are their main objectives, stakes, constraints, and instruments?

The actor analysis identifies six actor roles directly relevant to dynamic distribution grid tariffs: DSOs, consumers, electricity suppliers, BRPs, CSPs, and aggregators. Although these actors share an interest in a well-functioning electricity system, their objectives and ability to influence tariff outcomes differ. These differences create important requirements and trade-offs for tariff design.

For the DSO, the central objectives are to reduce congestion, improve the use of available network capacity, and maintain sufficient tariff revenues. Its instruments include tariff design, network monitoring, and congestion information, but its influence is constrained by regulation and dependence on consumer and market responses. Consumers value affordability, comfort, simplicity, and predictability. They can adjust electricity use, invest in flexible assets, or use automated control, although their access to flexibility and willingness to respond vary considerably.

Suppliers seek to limit implementation costs and operational burdens while maintaining viable customer services. Their instruments include billing systems, contract design, and consumer communication, despite their limited influence over the grid tariff itself. BRPs seek predictable portfolio demand and limited imbalance exposure, using forecasting, portfolio optimisation, and market adjustments to manage these risks. CSPs and aggregators seek viable business cases for flexibility services and can activate and coordinate distributed assets. Their ability to do so depends on controllable assets, reliable information and communication systems, and clear responsibilities. Aggregators could also reduce consumer complexity by translating tariff signals into automated operating decisions.

The stakeholder interviews reinforced these concerns while also revealing differences within actor groups, particularly between suppliers focused on commodity delivery and those offering flexibility services. Five cross-actor themes emerged: tariff predictability and financial-risk allocation; implementation complexity and differences in consumer flexibility; coordination with existing electricity-market signals; opportunities for new or expanded flexibility services; and the delineation of actor roles and responsibilities. Dynamic grid tariffs should therefore be treated as part of a broader market arrangement whose implementation depends on balancing these interconnected interests. These findings provide the basis for the design criteria developed in Chapter 5.

11.1.2 Subquestion 2

Which evaluation criteria can be derived from the literature and actor objectives and constraints to guide the design and evaluation of grid-tariff mechanisms?

Combining the literature with the actor analysis resulted in eleven evaluation criteria. Their scope can be explained through the four feasibility dimensions of Christensen et al. (2021). These dimensions are complementary: several criteria address more than one aspect of feasibility.

Technical feasibility concerns whether the mechanism provides an appropriate congestion signal and can function within the electricity system. This is addressed through congestion reflectiveness, interaction with other electricity-market signals, and the technical requirements captured by simplicity of

implementation.

Economic feasibility concerns the financial consequences for consumers, the DSO, and other market actors. Consumer cost exposure, cost recovery, and economic incentives assess these consequences directly, while limited additional burdens addresses the recurring operational demands imposed on participating actors.

Social feasibility concerns whether the mechanism is understandable and accessible to consumers with different capabilities. Clear purpose of the new system and low tariff volatility address the clarity and stability of the tariff signal. Consumer cost exposure, limited additional burdens, and non-discrimination also contribute to this dimension by addressing financial impacts, participation demands, and differences in tariff treatment.

Regulatory feasibility concerns the institutional organisation and principles governing tariff application. Delineation of actor roles addresses the allocation of responsibilities, while non-discrimination assesses whether comparable electricity behaviour receives comparable tariff treatment. These criteria inform the institutional assessment without constituting a full legal compliance assessment.

Together, these criteria ensure that the mechanisms are assessed beyond their congestion-related signals alone. Six criteria are evaluated quantitatively and five qualitatively, making trade-offs between system performance, financial outcomes, consumer considerations, and implementation requirements explicit.

11.1.3 Subquestion 3

What grid-tariff mechanisms can be designed to incentivize congestion-reducing behaviour through dynamic grid tariffs while mitigating the risks for grid users identified through the literature and actor analyses?

The design process resulted in seven mechanisms that combine congestion-related incentives with different approaches to risk mitigation. They were developed through a morphological analysis of four design dimensions: tariff structure, exposure limitation, time horizon, and role and risk allocation. Derived from the literature and actor analysis, these dimensions determine how the tariff signal is constructed, which demand is exposed, when tariff information becomes available, and how responsibilities and financial risks are distributed. Extreme configurations were used to explore the boundaries of the design space, followed by intermediate designs combining their characteristics.

Full EmPower provides unrestricted exposure to the hourly congestion-based tariff and serves as the benchmark for the alternative designs. Targeted EmPower restricts dynamic exposure to registered flexible assets, shielding other household demand from the congestion-dependent component. Ex-post Bonus retains the hourly signal but adjusts final payments through revenue redistribution. This changes the allocation of financial outcomes without guaranteeing lower costs for every household.

The two subscription mechanisms protect a predefined part of electricity use. Flex Volumetric applies dynamic charges once a monthly consumption allowance has been exceeded, while Flex Capacity applies them to electricity import above a subscribed capacity. The latter links exposure directly to household demand exceeding a capacity threshold. ADT instead modifies the signal itself by replacing hourly variation with predefined tariff blocks based on expected congestion patterns. The Capacity Steering Contract introduces contractual coordination of flexible assets, shifting part of the response from individual price-based decisions towards agreed control arrangements.

Together, these designs identify five complementary approaches to mitigating risk: restricting exposure to selected assets, shielding consumption through subscriptions, redistributing revenues after exposure, reducing short-term tariff variation, and allocating flexibility control through contracts. Each approach changes the balance between financial incentives, consumer exposure, predictability, and implementation requirements.

Full EmPower and the five alternative tariff mechanisms were evaluated against the Static reference. The Capacity Steering Contract remained a conceptual design because its evaluation required additional contractual assumptions that could not be established reliably from the available data. The resulting

design set therefore provides alternative ways of addressing the research objective, while the comparative evaluation determines their strengths and limitations.

11.1.4 Subquestion 4

How do alternative grid-tariff mechanisms perform for different household profiles and electricity market actors, based on the evaluation criteria defined in Step 2?

The evaluation shows that no mechanism performs best across all criteria. Quantitative model results and predefined qualitative assessments reveal differences in household costs, DSO revenues, flexibility incentives, and implementation requirements. Mechanisms were compared against the Static reference where applicable, without combining their performance into a weighted overall score.

Full EmPower closely reflects hourly congestion conditions but combines relatively high tariff volatility with a substantial revenue shortfall relative to Static. Targeted EmPower further reduces average household costs by shielding non-targeted demand from the dynamic component, but increases the revenue shortfall and introduces additional requirements for asset identification, measurement, and administration. Its distinction between types of electricity use also results in a less favourable non-discrimination assessment.

The calibrated subscription mechanisms produce revenues closer to the Static reference while limiting the share of consumption exposed to dynamic charges. Flex Capacity yields the highest sum of tariff-related flexibility benefits across the evaluated assets, with larger EV and battery benefits than Flex Volumetric but a smaller heat-pump benefit. Its battery benefit arises mainly from increased grid-tariff export remuneration, alongside reduced capacity-exceedance charges. The higher summed benefit therefore does not by itself establish greater physical congestion reduction. Both subscription mechanisms retain the variability of the underlying EmPower signal and protect consumers by limiting its application. Their revenue outcomes remain dependent on subscription calibration and population composition.

Ex-post Bonus restores aggregate reference revenues by construction while retaining hourly tariff variation. However, individual household outcomes differ substantially, and the additional redistribution step makes the relationship between hourly charges and final payments less straightforward to communicate. ADT reduces absolute tariff variation while preserving the same annual mean tariff as Full EmPower. This comes with lower congestion reflectiveness and a smaller summed tariff-related flexibility benefit, although the EV benefit is higher than under Full EmPower.

Household outcomes depend on consumption patterns, asset combinations, and their operation. CP1 (Consumer Profile 1) and CP2 face lower effective tariff burdens under every alternative mechanism, while CP5, which combines an EV and a heat pump without PV or battery storage, faces a higher burden. Its flexibility is not activated in the cost-exposure comparison, leaving potential opportunities to reduce costs. CP8 includes optimised battery operation and illustrates that lower grid-tariff payments do not necessarily imply lower total electricity costs. Across the separately evaluated assets, battery operation provides the largest total flexibility benefit under every mechanism.

For market actors, the mechanisms introduce different operational and coordination requirements. Suppliers face changes to billing, information processing, and consumer communication, while BRPs require predictable responses and coordination with other market signals. CSPs and aggregators gain potential opportunities to coordinate flexibility, but depend on viable incentives, reliable control systems, and clear responsibilities. Aggregators could reduce the complexity experienced by consumers through automation, although their service costs and contribution were not quantified. These actor effects are therefore assessed qualitatively rather than through a complete financial comparison.

Overall, the mechanisms expose trade-offs between consumer protection and flexibility incentives, household payments and DSO revenue recovery, tariff stability and congestion reflectiveness, and operational benefits and implementation complexity. Under the priorities adopted in this study, Flex Capacity provides the preferred direction for further development, while its practical value remains conditional on calibration, household outcomes, and the feasibility of implementation.

11.2 Main conclusion

What grid-tariff mechanism incorporating dynamic grid tariffs can be designed to provide effective incentives for congestion reduction while mitigating associated risks such as complexity and price volatility for electricity grid users?

Within the evaluated solution space, EmPower Flex Capacity provides the most promising design direction under the priorities adopted in this study. It combines a predefined capacity subscription with a congestion-dependent tariff applied to electricity imports above the subscribed capacity. This limits the share of household demand exposed to variable charges while retaining a financial incentive to reduce capacity exceedance, particularly during congestion hours when the congestion intensity raises the applicable tariff. Compared with a monthly volume allowance, the capacity threshold links exposure more directly to the level of household demand at a particular time.

The quantitative results support this preference, while also defining its limits. Under the selected calibration, Flex Capacity produces aggregate revenues close to the Static reference and the highest sum of tariff-related flexibility benefits across the evaluated assets. It provides larger EV and battery benefits than Flex Volumetric, although the heat-pump benefit is smaller. The detailed battery analysis shows reduced capacity-exceedance energy during congestion, but also shows that most of the battery's tariff benefit comes from export remuneration. Financial benefits therefore support the presence of incentives for flexible operation, rather than establishing the magnitude of realised network congestion reduction. Revenue recovery likewise remains dependent on subscription settings and consumer population composition.

Flex Capacity mitigates exposure to tariff volatility rather than reducing the volatility of the underlying signal. Consumption within the subscribed capacity is shielded from variable import charges, while exceedance remains exposed to the EmPower tariff. This protection does not guarantee a lower annual bill for every household. Its value depends on the subscribed capacity, consumption pattern, and available flexibility.

The principal trade-off is implementation complexity. Subscription administration, metering-data processing, communication, and billing require technical and organisational arrangements, together with clear actor responsibilities. As identified in the actor analysis, aggregators could help consumers participate by translating tariff signals and subscription limits into automated and/or steered control of EVs, heat pumps, and batteries. This could allow households to benefit from flexibility without continuously monitoring tariffs or adjusting individual assets, while respecting their comfort requirements and preferences. Consumer-facing simplicity could therefore coexist with a relatively complex tariff mechanism. However, this would shift part of the operational burden to service providers rather than eliminate it, and its practical value would depend on service costs, reliable control systems, and clear agreements on responsibilities. The contribution of aggregation has not been quantified in this study.

ADT remains a relevant alternative where tariff stability and a longer information horizon receive greater priority. Its predefined blocks reduce absolute tariff variation, but also reduce congestion reflectiveness and the summed tariff-related flexibility benefit. Its current calibration additionally leaves a substantial revenue shortfall relative to Static. ADT could serve as an intermediate step towards more dynamic mechanisms, but this would require revenue recalibration and an assessment of whether its systems and processes support a later transition to capacity subscriptions. Such a pathway has not been tested in this study.

The main conclusion is therefore that selective exposure through a capacity subscription offers a promising way to combine congestion-related financial incentives with protection from unrestricted dynamic charges. Flex Capacity is preferred within the assumptions and priorities of this research, rather than established as a universally optimal or implementation-ready solution. Further testing with representative consumer data, alternative network conditions, and explicit network responses is needed to determine whether its financial advantages translate into effective congestion relief at acceptable implementation costs.

11.3 Practical implementation

The preferred design should not be interpreted as a mechanism that can be implemented immediately at full scale. Instead, the findings suggest that the transition towards more congestion-responsive grid tariffs can follow a gradual implementation pathway in which different mechanisms fulfil different roles during the transition.

A practical first step could build further on the voluntary character of the current EmPower approach. Consumers who already have a dynamic electricity contract may form a suitable initial target group, as they are already familiar with time-varying price signals and may have a greater incentive and ability to optimise flexible electricity use. Suppliers, CSPs, and aggregators could support this process by incorporating the congestion-related grid tariff into existing optimisation services. The interviews indicate that these market parties already operate in environments characterised by short trading horizons, changing price signals, and frequent optimisation decisions. Dynamic grid tariffs may therefore create additional opportunities for flexibility optimisation rather than only additional implementation burdens.

Within such a voluntary setting, Full EmPower can remain a relevant congestion-management instrument despite its relatively weak tariff-revenue recovery under the simulated network conditions. The cost-recovery indicator used in this research only compares tariff revenues with the static reference case and does not capture the wider economic value that congestion-responsive behaviour may create for the DSO. Flexible demand may free network capacity for additional connections and reduce or postpone expenditures on grid reinforcement or other congestion-management measures. The practical DSO business case should therefore consider these wider network benefits alongside tariff revenues rather than interpreting lower tariff revenues as evidence that the mechanism itself is undesirable.

For broader adoption, a more predictable mechanism such as the Adaptive Dynamic Tariff could provide an intermediate step. Its periodically defined tariff blocks expose consumers and market actors to congestion-related differences while reducing short-term tariff volatility and requiring less complex administration than a capacity subscription. ADT could therefore be used to familiarise a broader consumer group with time-dependent and locally differentiated grid tariffs before introducing more sophisticated exposure-limiting mechanisms. Before such a pathway could be adopted, ADT would require revenue recalibration and an assessment of whether its technical and administrative arrangements support a subsequent transition to capacity subscriptions.

At the same time, Flex Capacity should be further developed through targeted pilots as a potential long-term mechanism. Such pilots should test not only whether capacity-based exposure creates measurable peak reduction, but also how the mechanism functions organisationally. Important aspects include the calibration of subscription levels and fees, consumer understanding of capacity expressed in kW, subscription choice, and the allocation of responsibilities for tariff determination, subscription administration, communication, billing, and settlement. Suppliers, CSPs, aggregators, or other service providers could support consumers in selecting and managing an appropriate capacity subscription based on historical demand and available flexibility. Automation through HEMS or similar optimisation services could further reduce the need for continuous active consumer response.

Practical implementation also requires reliable information exchange between the actors involved. Consumers and flexibility providers need sufficiently early tariff information to respond, while suppliers and BRPs need to anticipate changes in demand. Increasing the publication horizon requires forecasts of future network conditions, creating a trade-off between predictability and congestion reflectiveness. Pilot projects should therefore test different communication horizons and develop procedures for forecast errors, communication failures, and situations in which intended flexibility cannot be activated. Clear responsibilities for data provision, optimisation, billing, and flexibility activation should be established before large-scale implementation.

A staged implementation strategy would allow the mechanisms to be refined using practical evidence before broader deployment. Voluntary Full EmPower participation can provide experience with highly congestion-reflective pricing among consumers and market parties that are already accustomed to dynamic signals, while ADT can provide a more accessible transition towards time-dependent grid tariffs. In parallel, Flex Capacity can be piloted and calibrated as a longer-term mechanism that combines protection against unrestricted dynamic exposure with a strong incentive to reduce peak

demand during congestion. This approach would allow Stedin to evaluate not only tariff revenues, but also realised congestion reduction, additional network capacity created, consumer acceptance, market-party participation, and the wider economic value of congestion-responsive behaviour.

Taken together, these implementation pathways provide Stedin with a structured basis for further piloting and refinement, allowing practical evidence on congestion reduction, consumer response, market coordination, and network value to inform the gradual development of a more efficient, reliable, and future-proof distribution grid.

12 Personal reflection

Completing this thesis has been a challenging, but also highly interesting and rewarding process. The subject proved to be both technically complex and highly relevant, particularly given the rapidly changing electricity system and the increasing occurrence of grid congestion. Working at Stedin gave me the opportunity to become much more familiar with the role of a distribution system operator and with the many technical, organisational, and market-related processes involved in maintaining and developing the electricity grid.

One of the main challenges at the beginning of the research was understanding the full scope of the problem. Dynamic grid tariffs interact with many different actors, grid-tariff mechanisms, consumer behaviours, and technical constraints, and it was initially difficult to determine which aspects should be included in the research and which should remain outside its scope. Several choices made during the early stages therefore had to be reconsidered later in the process. I also found it challenging to define a clear research structure from the start. As my understanding of the problem developed, the research approach and several methodological steps were refined. This resulted in some unanticipated and time-intensive stages, but it also taught me the importance of continuously evaluating whether the chosen research approach still fits the research objective.

Working within the Innovation team at Stedin helped me considerably throughout this process. Being surrounded by people working on improving the energy system helped me remain focused and provided insights that extended far beyond the direct scope of my thesis. In particular, the interviews with households participating in the EmPower pilot made the topic much more touchable. They showed me how a tariff mechanism that may appear relatively straightforward in a model can affect people differently in practice. The interviews with market parties similarly broadened my understanding of the electricity system and demonstrated how strongly technical design choices are connected to commercial, organisational, and behavioural considerations.

Discussions with my supervisors, colleagues, friends, and family also played an important role in the development of the thesis. These conversations repeatedly encouraged me to step back from individual calculations or design choices and reconsider the broader problem. This helped me to look at the research from different perspectives and improved both my understanding of the problem and the quality of the final design process. One of the most rewarding moments was reaching the stage where the different results started to form a coherent overall picture. At that point, the trade-offs between the mechanisms became clearer and I became increasingly enthusiastic about how the research could contribute to the further development of dynamic grid tariffs.
The final weeks of the thesis were quite demanding, but I am very satisfied with both the process and the final outcome. Looking back, I would approach the initial scoping and research planning more explicitly if I were to start the project again, as clearer boundaries and a more detailed methodological structure could have prevented several iterations later in the process. At the same time, these iterations were also an important part of the learning process and contributed to a much deeper understanding of the subject.

Finally, I am very grateful to my supervisors Laurens de Vries, Niek Mouter, and Mareno de Kort for their guidance, critical questions, and constructive feedback throughout the project. I particularly appreciated the combination of critical feedback with a consistently positive and encouraging supervision style. I am also thankful to the Innovation team at Stedin, and especially the EmPower project team, for providing a comfortable working environment and for teaching me much more than only the subject matter of this thesis. Although certain periods of the project were challenging, I look back positively on the process and on everything I learned along the way.

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Appendix

A Analytical table

Table 35: Literature analysis

Year	Author	Theme	Methodology	Mechanism	Key contribution	Limitations
2023	Alavijeh et al.	Congestion management & coordination	Qualitative framework and ESOOP modelling platform	LFMs, LEMs and bilateral flexibility contracts	Shows how market-based coordination mechanisms can complement dynamic tariffs by activating local flexibility.	More realistic testing is required for practical implementation.
2023	Wang et al.	Tariff design	Design framework and literature-based assessment	Fixed, volumetric and capacity charges	Distinguishes the main network-tariff components and provides a structural classification for tariff design.	Broad framework; does not evaluate specific congestion-based dynamic tariffs.
2024	Winzer & Hensler-Ludwig	Tariff design	Linear optimisation model	Fixed, volumetric and capacity-based grid tariffs	Further distinguishes the main tariff structures and their design characteristics.	Primarily applicable to tariff classification rather than dynamic congestion tariffs.
2024	Schittekatte et al.	Tariff design	Time-series analysis and load-shifting optimisation	ToU, CPP and dynamic/locational pricing	Distinguishes static and dynamic pricing and shows how temporal differentiation can incentivise flexibility.	Results depend on assumed flexible loads and market conditions.
2022	Hennig et al.	Tariff design & evaluation	ANTS model and quantitative performance assessment	Static tariffs, ToU, capacity subscription and dynamic tariffs	Identifies trade-offs between efficiency, cost reflectiveness, simplicity and consumer impacts.	Performance is context-dependent and practical trade-offs require further research.
2013	Dütschke & Paetz	Tariff design & consumer response	Questionnaire and field experiment	ToU, RTP and CPP	Shows differences in consumer response and the importance of comprehensibility and predictability.	Underlying motives for consumer preferences remain insufficiently understood.
2024	Boontagool & Wirasanti	Tariff design	Distribution-network simulation	Adaptive Dynamic Tariff	Introduces periodically updated tariff periods as an intermediate option between ToU and RTP.	High complexity may hinder practical implementation.
2024	Hinchberger et al.	Tariff design & economic incentives	Empirical analysis and scenario modelling	RTP	Shows that RTP can better align consumer prices with marginal system costs and incentivise demand response.	Benefits depend on consumers' ability to understand and respond to rapidly changing prices.
2025	Neuhoff et al.	Locational tariff design	Qualitative market review	Nodal pricing / Locational Marginal Pricing	Shows that locational pricing can improve spatial price signals and reward flexibility in congested areas.	Large-scale adoption requires substantial institutional and market redesign.
2022	Fabra et al.	Tariff risk mitigation	Literature review	RTP, reliability options and strike prices	Shows how strike prices can limit extreme price exposure while retaining scarcity incentives.	Developed primarily for wholesale electricity markets.

References

Year	Author	Theme	Methodology	Mechanism	Key contribution	Limitations
2022	Batlle et al.	Tariff risk mitigation	Literature review and theoretical model	Price/bill caps and revenue redistribution	Shows how caps and redistribution can reduce extreme consumer exposure while retaining price incentives.	Designed primarily for wholesale electricity-price risk.
2024	Ormeño et al.	Hybrid tariff mechanisms	Quantitative assessment of SPOT, PVPC and local-market scenarios	Dynamic tariffs, capacity charges and local markets	Shows how dynamic tariffs can be combined with local flexibility markets to address remaining congestion.	Interactions between tariffs and local markets remain complex.
2022	Shen et al.	Tariff design	Two-level MINLP model	Dynamic tariffs + Scheduled Reprofiling Products	Combines dynamic tariffs and coordinated flexibility through an aggregator to improve congestion management.	High modelling and coordination complexity may limit implementation.
2020	Hennig et al.	Tariff design	Distribution-network simulation	Capacity subscription / dynamic capacity contract	Shows how subscribed capacity can improve predictability while retaining incentives related to peak demand.	Requires forecasting and additional coordination between market actors.
2023	van der Holst et al.	Tariff design	Simulation using Kubernetes and ESDL	Dynamic bandwidth tariff	Demonstrates a capacity-oriented tariff using predefined bandwidths and additional charges for exceedance.	Further testing across network topologies and operating conditions is required.
2012	Roozbehani et al.	Price volatility & system response	Non-linear modelling and numerical RTP simulations	Price volatility / demand-supply feedback	Shows how feedback between prices and demand response can amplify fluctuations and create price spikes.	Uses a stylised consumer model without explicit storage or load-shifting dynamics.
2020	Matisoff et al.	Consumer risk & flexibility	Literature review	Dynamic pricing, ToU, RTP, CPP and VPP	Shows that inflexible consumers have fewer opportunities to respond to volatile prices.	Focuses on broader dynamic-pricing barriers rather than dynamic grid tariffs specifically.
2022	Lee et al.	Price-risk mitigation	Machine-learning-based framework and demand-response modelling	Price-risk mitigation instrument	Supports the need for mechanisms that mitigate exposure to volatile electricity prices.	Post-response system states may remain sensitive to small demand changes.
2011	Balamurugan & Srinivasan	Network modelling	Power-flow / distribution-system modelling	Physical grid operation	Illustrates power-flow modelling for assessing physical network conditions such as voltages and power flows.	Focuses on technical network behaviour rather than consumer tariff response.
2023	Jha et al.	Network modelling	Power-flow / system optimisation	Distribution-network operation	Illustrates modelling focused on physical network constraints and system operation.	Provides limited insight into consumer financial exposure and tariff incentives.
2022	Blaschke	Consumer response & uncertainty	Mixed-integer linear programming	Dynamic pricing and varying energy taxes	Shows how dynamic pricing affects household response, financial stability and investment certainty.	Limited insight into willingness to manually shift demand and distributional effects.

References

Year	Author	Theme	Methodology	Mechanism	Key contribution	Limitations
2022	Miletić et al.	Consumer flexibility & automation	Mixed-integer linear programming	ToU and RTP	Shows that flexible and automated households can benefit more from dynamic pricing than inflexible households.	Represents a limited range of realistic household behaviours and characteristics.
2023	Gunkel et al.	Consumer heterogeneity	Statistical analysis of a large dataset	Consumer load profiles / flexibility	Demonstrates substantial heterogeneity in electricity demand and flexibility across consumer groups.	Limited comparison across socio-economic consumer groups.
2025	Sironja et al.	Coordination, aggregation & risk mitigation	Financial ROI analysis	Energy sharing and collective self-consumption	Shows that collective energy use can reduce individual price exposure and support coordinated flexibility.	Results depend on consumer diversity and pricing arrangements.
2019	Mehrjerdi & Hemmati	Flexibility modelling	System-level optimisation	Battery storage / flexible assets	Shows how battery operation can be optimised while accounting for technical and network constraints.	More technically detailed than required for household tariff simulation.
2017	Hesse et al.	Household flexibility modelling	Household-level optimisation	PV-battery system	Supports explicit modelling of flexible residential PV and battery assets.	Focuses on a specific PV-battery configuration rather than heterogeneous households.
2023	Selim et al.	Household flexibility modelling	Cost-minimisation optimisation	Battery scheduling under dynamic prices	Provides a methodology for price-responsive battery scheduling subject to power, capacity and efficiency limits.	Focuses on battery scheduling rather than wider tariff and actor effects.
2022	Pototschnig et al.	Tariff-based risk mitigation	Literature review and system analysis	Fixed-price base quantity combined with RTP	Proposes combining a protected base quantity with dynamic pricing for deviations.	Policy-oriented and primarily focused on wholesale electricity markets.
2021	Christensen et al.	Evaluation framework	Literature-based evaluation framework	Technical, economic, social and regulatory feasibility	Provides four overarching feasibility dimensions for structuring tariff evaluation.	Does not provide detailed operational indicators specifically for dynamic grid tariffs.
2017	Abdelmotteleb et al.	Evaluation framework	Tariff evaluation framework / comparative assessment	Cost recovery, reinforcement savings, consumer response and side-effects	Adds criteria covering network benefits, efficient response and unintended consumer impacts.	Does not fully capture actor-specific implementation and coordination requirements.
2026	Muğaloğlu et al.	Price volatility & uncertainty	Price modelling using an ARIMA model	Electricity-price volatility / investment uncertainty	Shows that price volatility increases uncertainty and can affect investment decisions.	Limited to the Turkish day-ahead market between 2018 and 2024.
2022	Goedegebure & Hennig	Tariff uncertainty & predictability	Autoregressive price-forecasting model	Tariff forecasting & capacity subscription	Shows that earlier price information enables longer optimisation horizons and can improve tariff performance.	Does not fully represent non-linear consumer behaviour and uncertainty.

References

Year	Author	Theme	Methodology	Mechanism	Key contribution	Limitations
2022	Bjarghov et al.	Consumer acceptance	Tariff and local-market analysis	Dynamic grid tariffs and local electricity markets	Highlights consumer acceptance and perceived fairness as conditions for tariff implementation.	Provides less insight into wider market-role and coordination effects.
2021	Boom & Schwenen	Consumer acceptance & tariff preferences	Consumer-oriented economic analysis	RTP	Shows that consumers value understandable tariffs, cost protection, clear purpose and limited effort.	Primarily focuses on consumer preferences under RTP.
2014	Ruester et al.	Actor roles & regulation	Regulatory / institutional analysis	Role of DSOs in smart distribution systems	Explains the changing responsibilities of DSOs in operating and coordinating distribution systems.	Does not specifically address dynamic grid-tariff mechanism design.
2023	Winther & Sundet	Consumer heterogeneity & fairness	Stakeholder and household perspective analysis	Dynamic grid tariffs / flexibility	Shows differences in consumers' ability to respond due to flexibility, resources and technology access.	Focuses mainly on household and stakeholder perspectives.
2019	Fotouhi Ghazvini et al.	Automation & congestion management	Market-based mechanism using HEMS	HEMS, dynamic tariffs and DTP	Shows how HEMS can automate flexible household response to dynamic price signals and support congestion management.	Uncertainty in congestion-management performance remains insufficiently addressed.
2025	García et al.	Actor roles & coordination	Review / analysis of aggregator relationships	Aggregators and demand-response services	Shows the growing coordination role of aggregators in increasingly interconnected electricity markets.	Rapidly changing market roles make institutional relationships context-dependent.

Table 35: Analytical table

References

B Summarised Interview Transcripts

This appendix presents summarised transcripts of the stakeholder interviews conducted during this research. The summaries are based on the original interview transcripts and interview notes. Repetitions, conversational elements, and sections without substantive relevance to the research have been omitted. The original Dutch interview material has been translated into English and paraphrased while preserving the main arguments, concerns, and design considerations expressed by the interviewees. The summaries should therefore not be interpreted as verbatim transcripts.

The interviews were used to complement the literature-based actor analysis and to identify practical requirements, concerns, and opportunities related to dynamic grid tariffs. Some organisations were interviewed more than once. In these cases, the interviews are presented separately because the later interviews focused more specifically on potential mechanism designs.

B.1 Distro Energy

The interviewee identified consumer risk aversion as an important barrier to the adoption of dynamic tariffs. Consumers may focus primarily on the possibility of very high prices, even though dynamic tariffs can also result in periods of very low costs. At the same time, the current electricity system provides consumers with limited direct financial feedback regarding the consequences of their consumption behaviour. More direct and individual price signals could therefore improve the relationship between consumer behaviour and actual system conditions.

A practical difficulty is that forecasting and settlement are currently based on relatively aggregated consumption information. More detailed consumer-level data and suitable digital infrastructure would be required to allocate the financial consequences of behavioural changes more directly. However, the financial differences for individual small-scale consumers may remain relatively small. Consequently, price signals alone may not always be sufficient to initiate behavioural change. Additional congestion-related rewards or other mechanisms could therefore be required to make flexibility sufficiently attractive.

According to the interviewee, the longer-term purpose of dynamic tariffs should be to encourage investment in flexibility. Consumers could, for example, invest in batteries or other flexible technologies that allow them to maintain their preferred lifestyle while responding to system conditions automatically. The consumer should ultimately remain responsible for deciding whether to invest in flexibility or accept higher costs. The DSO should primarily focus on operating and expanding the network, while market parties can develop services that enable consumers to respond.

The interviewee was therefore cautious about mechanisms that strongly limit dynamic price exposure. Applying strict price caps or fully insuring consumers against high tariffs may weaken the behavioural signal that the tariff is intended to create. Some form of risk protection could nevertheless be possible if consumers explicitly pay for this protection, for example through a higher premium. This would preserve the economic distinction between consumers who respond to congestion signals and consumers who choose greater price certainty.

Distributional effects were also considered important. Consumers with fewer financial resources may have less ability to invest in flexibility technologies. Targeted financial support, subsidies for flexibility assets, or collective solutions such as neighbourhood batteries could help broaden access to flexibility. The interviewee therefore recommended considering behavioural and socio-economic factors alongside the economic design of dynamic tariffs.

B.2 Eneco

The interviewee expressed substantial concerns regarding the comprehensibility of dynamic grid tariffs for residential consumers. Grid congestion is already an abstract concept for many households, and translating this into frequently changing grid tariffs introduces additional complexity. Consequently, it may be unrealistic to expect consumers to actively optimise their behaviour themselves. Automation

or energy services provided by suppliers could therefore become important for enabling an effective response.

A related concern is the distributional impact of dynamic tariffs. Consumers differ substantially in their ability to respond, and households with little flexibility may face higher costs without having a realistic opportunity to avoid them. This could contribute to energy-poverty concerns. Before introducing additional protection mechanisms such as price caps, however, the actual magnitude of the financial risk created by dynamic grid tariffs should be established, since grid tariffs may be less volatile in absolute terms than wholesale electricity prices.

Hourly or more granular tariffs were considered particularly demanding for consumers. Such tariffs would likely require automated optimisation because the financial benefit from manually monitoring hourly tariff changes may be too small relative to the effort required. Day-ahead publication could improve predictability, but would not remove the underlying complexity.

Eneco could potentially take a service-provider or aggregation role by optimising consumer assets on behalf of households. The organisation has the knowledge and scale required for such a role. However, the introduction of additional parties that can influence household demand also introduces market-coordination risks. Suppliers purchase electricity based on expected consumption, while BRPs are responsible for maintaining portfolio balance. If an independent aggregator changes consumer behaviour without sufficient coordination, suppliers and BRPs can face additional forecasting and imbalance risks.

The interviewee therefore emphasised the importance of accurate data and clear allocation of responsibilities. Questions arise regarding who controls flexible assets, how consumer comfort is protected, how contractual responsibilities are distributed within an aggregation, and how the actions of third parties are coordinated with suppliers and BRPs. The emerging aggregator role is institutionally possible, but requires careful integration into the existing market structure.

A mechanism in which financial protection is converted into a credit for investment in flexibility was considered an interesting direction. However, such an approach could still create affordability problems because flexibility technologies require an initial investment. Overall, consumer understanding, automation, distributional impacts, data availability, and clear market coordination were identified as important conditions for implementation.

B.3 Energie Nederland

The interviewee interpreted dynamic grid tariffs as a form of congestion management at the low-voltage level. From this perspective, an important question is whether the existing supplier model remains the most appropriate structure or whether the DSO should take greater responsibility for administering congestion-related mechanisms.

Three characteristics were identified as particularly important for a future tariff system: clarity, practical feasibility, and explainability. The time horizon of tariff information is closely related to these characteristics. If tariff levels are determined only shortly before delivery, consumers and market parties have limited opportunities to anticipate and respond. This also complicates the business case for intermediary parties that would be required to absorb or manage tariff risk without knowing future tariff levels. For very short-term congestion management, direct procurement of flexibility by the DSO could therefore be more practical because the DSO possesses the relevant information on local network conditions.

The interviewee was cautious about assigning a central insurance or aggregation role to a CSP. Individual CSPs may lack the scale advantages required to manage large numbers of residential consumers. Building the necessary systems and portfolio size would require considerable time and investment.

A possible alternative would be a structure in which consumers can choose between fixed, flexible, or dynamic arrangements directly associated with their grid use. However, such mechanisms also

raise distributional concerns because consumers differ in their ability to respond to tariffs. A system coordinated more directly by the DSO could potentially address local congestion more consistently, although this would require further institutional development.

Finally, the interviewee stressed that alternative mechanisms should be evaluated by comparing their societal benefits with their implementation complexity and costs. Potential savings from avoided or delayed grid reinforcement should therefore be considered alongside investments required from DSOs and market parties to implement a new tariff structure.

B.4 Energie VanOns – Interview 1

The interview focused strongly on the allocation of risk and responsibilities under dynamic grid tariffs. Residential consumers and energy communities generally prefer limited financial risk, while many consumers also have relatively little ability or willingness to actively manage their electricity use. This creates a potential role for energy service providers that can organise administrative processes and flexibility on behalf of consumers or energy communities.

An important design choice concerns where dynamic tariff risk is allocated. Consumers could be directly exposed to the tariff, or they could pay a relatively stable fee while a supplier, BRP, or another service provider manages the remaining risk. The interviewee noted that intermediate structures can be difficult to organise. A relatively clear distinction exists between consumers carrying the full tariff risk themselves and consumers purchasing greater price certainty from another party. Price caps or stop-loss-type arrangements could potentially provide an intermediate solution when future costs are uncertain.

The existing supplier model was identified as an important implementation concern. Suppliers already collect network charges from small-scale consumers and carry administrative and collection responsibilities without necessarily being compensated for additional complexity. Even relatively simple Time-of-Use tariffs require changes to billing systems and lead to consumer questions. More dynamic tariffs could substantially increase these burdens. Alternative billing arrangements, including a more direct role for the DSO, may therefore deserve consideration.

Energy communities were considered a potentially relevant environment for dynamic tariffs. A collective could coordinate flexible assets and distribute responsibilities among consumers, an energy service provider, and the DSO. However, this raises questions regarding consumer choice, contractual obligations, and whether a sufficiently large share of households within a constrained network area participates. A fragmented set of suppliers or service providers may reduce the effectiveness of local coordination.

The interviewee also highlighted new commercial opportunities for suppliers. Traditional electricity supply is increasingly supplemented by services such as monitoring, battery optimisation, PV services, insulation, and coordinated control of household assets. Dynamic grid tariffs could strengthen the business case for such services. Nevertheless, predictable tariffs and reliable data remain essential. The required data infrastructure needs substantial standardisation before highly dynamic mechanisms can be implemented at scale.

For very small flexible loads, the economic value of active optimisation may be insufficient to justify the required investment. Larger flexible assets and collective approaches may therefore be more promising. A longer-term development path could involve cooperation between energy communities, DSOs, and energy service providers, with flexibility increasingly coordinated at the local level.

B.5 Energie VanOns – Interview 2

The follow-up interview focused on several concrete tariff design options. Implementation costs, comprehensibility, behavioural predictability, data availability, and the timing of tariff publication were identified as important considerations. The basic principle that electricity use becomes more expensive when the network is congested was considered understandable for consumers, although the

surrounding market and settlement arrangements may be considerably more complex.

For suppliers, tariff information should be provided through a simple and centralised data infrastructure. Timing is particularly relevant because tariff information needs to be available before important market nomination deadlines. The interviewee therefore stressed that information provision should be incorporated explicitly into the mechanism design.

A capacity subscription was regarded as a promising option, particularly when combined with an Energy Management System. Consumers could select a capacity level and receive greater price certainty within that subscription, while retaining an incentive to limit peak demand. An important design question is what happens when the subscribed capacity is exceeded. The interviewee favoured applying the dynamic component specifically when network conditions actually require it rather than penalising exceedance continuously.

Asset-specific tariffs were also discussed. Targeting flexible technologies such as EVs, PV systems, heat pumps, and batteries could focus incentives on the largest sources of flexibility. EV charging was considered particularly relevant because charging peaks tend to persist for longer periods. However, common optimisation signals may cause many consumers to shift simultaneously towards the same cheap hours, potentially creating new peaks. Coordination or direct activation by a supplier or DSO could therefore be more effective than relying solely on uniform price optimisation.

A local Time-of-Use system could provide greater predictability but would still require substantial implementation effort. If infrastructure for granular tariffs is developed, the interviewee suggested designing it sufficiently flexibly to allow tariff blocks to become more dynamic over time.

Finally, a reward-only or Contract-for-Differences-type structure was considered potentially too weak to generate sufficient behavioural response. According to the interviewee, either financial incentives need to be sufficiently strong in both directions or flexibility needs to be activated more directly when congestion reduction is required.

B.6 ENGIE – Interview 1

The interviewee distinguished between the regulated network domain, which traditionally provides a relatively stable foundation, and the competitive electricity market, where prices and market positions are already more volatile. Introducing highly dynamic grid tariffs would make the regulated component more volatile as well, potentially increasing uncertainty throughout the wider electricity market. A relatively stable Time-of-Use structure with pronounced peak and off-peak periods was therefore considered easier to communicate and implement.

Complexity was identified as one of the main challenges of congestion-based tariffs for residential consumers. Consumers generally understand the concept that using a congested system at busy moments should be more expensive, but detailed congestion management is much less tangible. This is particularly relevant for households with limited flexibility. Consumers with greater technological flexibility may be better able to avoid high-tariff periods, which creates questions regarding proportionality and fairness.

From the supplier perspective, additional complexity results directly in additional costs. Consumers generally contact their supplier when they have questions about their energy bill, meaning that complicated grid tariffs increase customer-service requirements even when the supplier does not determine the tariff itself. ENGIE nevertheless also sees potential opportunities in providing optimisation services. By combining electricity prices, network tariffs, and flexible consumer assets, energy service providers could help consumers respond without requiring continuous manual action.

The interviewee stressed that market parties need to be involved early in tariff design. A mechanism developed primarily from the network-operator perspective may underestimate the consequences for suppliers and other market roles. The consumer, rather than the DSO, should remain central when designing the market structure.

The existing supplier model was also questioned. Requiring many suppliers to adapt their billing systems for a relatively limited group of consumers participating in a dynamic tariff pilot may lead to disproportionate implementation costs. Direct collection of dynamic grid charges by the DSO could therefore be worth considering. It could also make clearer to consumers which part of their bill relates to network use.

Large-scale implementation would require a substantial development and testing period and significant investment. Therefore, sufficient certainty regarding the value and functioning of the mechanism is required before market parties make these investments. Overall, complexity and proportionality or fairness were identified as the most important criteria. A Time-of-Use structure with clearly distinguishable peak and off-peak periods was considered the most understandable near-term approach.

B.7 ENGIE – Interview 2

The second ENGIE interview focused on specific design alternatives. Implementation costs, comprehensibility, and behavioural predictability remained important concerns. The interviewee also stressed that the effectiveness of any price mechanism depends on how the incentive is constructed and how it interacts with the actions of other market parties.

A capacity subscription was considered capable of providing greater cost stability while maintaining an incentive to limit capacity use. Consumers could select a lower subscription and retain an incentive to remain within the corresponding capacity, while consumers seeking greater certainty could purchase a higher subscription. However, the analogy with a conventional subscription is incomplete because several market actors may simultaneously be active on the same electricity connection. Grid tariffs, wholesale-market incentives, BRP positions, and flexibility services can therefore create interacting or potentially conflicting signals. Reliable data exchange and coordination between these parties would be necessary for a capacity-based mechanism to function effectively.

The interviewee also questioned the extent to which local low-voltage congestion will develop and whether highly local tariffs will always be justified. The interaction between congestion at different network levels and other tariff signals should therefore be considered carefully.

Asset-specific tariffs could focus dynamic exposure on technologies such as PV, heat pumps, EVs, and batteries, thereby targeting consumers with greater flexibility. However, this requires detailed asset data, appropriate permissions, and a suitable legal basis. Particular care would be required to avoid exposing consumers without realistic behavioural options to additional costs.

Local Time-of-Use tariffs determined at transformer level could provide more predictable congestion-related signals than fully dynamic tariffs. However, predicting consumer behaviour remains difficult and locational differentiation can introduce fairness or non-discrimination concerns between households in nearby areas.

Finally, strike-price structures and price caps were discussed as methods of limiting financial risk. Such mechanisms could protect consumers but add additional complexity and may face regulatory or political challenges. The interview therefore reinforced the broader trade-off between strong congestion-reflective incentives, consumer protection, and practical market coordination.

B.8 Frank Energie

The interviewee expressed a strongly positive view of dynamic electricity prices and dynamic grid tariffs. Frank Energie's business model already combines dynamic electricity contracts with automated optimisation of flexible assets such as EVs, heat pumps, batteries, PV systems, and other controllable loads. From this perspective, congestion-based grid tariffs create an additional economic signal that can be incorporated into existing optimisation services.

Automation was considered essential. Rather than expecting consumers to monitor individual tariff components, a supplier or energy service provider can optimise assets automatically based on the

combined electricity price and grid tariff. Dynamic grid tariffs can consequently strengthen the business case for flexible technologies such as batteries by increasing the value of shifting consumption away from congested periods.

The interviewee was also positive about locally differentiated tariffs. If congestion differs between transformers or neighbourhoods, local tariffs can provide targeted incentives in precisely those areas where flexibility is required. Day-ahead tariff information was considered sufficient for a digitally oriented supplier to incorporate the grid signal into automated control algorithms.

Consumer-facing complexity was not viewed as the primary barrier. The interviewee argued that consumers do not necessarily need to understand every component of the tariff if suppliers present a clear all-in electricity price in an application. Experiences with dynamic and Time-of-Use tariffs in other European markets were used to illustrate that underlying tariff complexity can be translated into a relatively simple consumer interface. From this perspective, the larger implementation barrier may lie with suppliers that need to adapt legacy systems rather than with consumers themselves.

For consumers with limited active flexibility, clear presentation of price information could still stimulate simple behavioural changes, although the largest congestion benefits were expected from automated control of major flexible assets. Consumers with fixed contracts would therefore also require accessible information, for example through an application or notifications.

The interviewee was more cautious about optional mechanisms that allow consumers to avoid the dynamic signal through an intermediary or insurance structure. If consumers can choose between a strongly congestion-reflective tariff and an alternative with lower risk and weaker incentives, market segmentation may occur. Consumers may systematically choose the alternative that provides greater protection while contributing less flexibility. This could weaken the effectiveness of the mechanism.

Finally, dynamic tariffs were also viewed as an opportunity for households with relatively low consumption, since the current fixed network tariff does not differentiate according to grid use. Nevertheless, households with limited financial resources may require support to obtain flexibility technologies. Small batteries or combinations of PV and storage were suggested as potential ways of expanding the ability of these households to respond.

B.9 Groendus

The interviewee approached dynamic grid tariffs primarily from the perspective of congestion services, market coordination, and the organisation of flexibility. Previous experience with the development of market communication structures that contributed to the current GOPACS framework highlighted the importance of explicitly defining new market roles, communication processes, and operational conditions when introducing congestion-management mechanisms.

Particular attention was given to the development of contractual flexibility products. The interviewee referred to the development from earlier capacity-limiting arrangements towards Capacity Steering Contracts (CSC), which allow flexibility to be activated more specifically in response to congestion and can operate in both consumption and production directions. Such mechanisms differ from purely price-based tariffs because the conditions under which flexibility is activated are defined contractually.

The interviewee stressed that the central challenge is not only the design of the financial incentive but also the coordination between the large number of stakeholders involved. Questions regarding the conditions under which the mechanism applies, penalties, communication, and responsibilities need to be resolved before a congestion product can be rolled out at scale.

Different network operators may have different preferences and development speeds, while market parties need sufficient standardisation to implement services efficiently. From the Groendus perspective, an important practical criterion is therefore whether a mechanism can be operationalised and scaled across the market rather than functioning only in an isolated pilot.

B.10 Pure Energie

The interviewee considered the desirability of dynamic grid tariffs to depend strongly on the electricity contract and the flexibility available to consumers. Consumers who already have a dynamic electricity contract could face simultaneous high electricity prices and high grid tariffs during certain periods, increasing their total price exposure. This could unintentionally make fixed electricity contracts more attractive. The interaction between grid tariffs and electricity-price signals should therefore be explicitly considered.

Dynamic grid tariffs could nevertheless function as a transitional mechanism towards a more flexible electricity system. They can increase awareness of peak demand and encourage consumers to recognise the value of flexibility. In a future system, suppliers could increasingly operate as energy service providers that help consumers optimise batteries and other flexible technologies rather than focusing solely on commodity supply.

A major concern is whether households can actually respond to the tariff signal. Many consumers cannot continuously monitor their electricity consumption, may not be at home during the day, or may have limited financial resources to invest in flexibility. Highly dynamic tariffs could therefore create affordability or energy-poverty concerns. Subsidising small batteries or other flexibility technologies could improve the ability of such households to respond, although this would require additional policy intervention.

Transparency was considered essential. Consumers need to understand both the purpose of the tariff and its financial consequences. Unexpected annual or monthly bills could undermine acceptance, particularly for financially vulnerable households. Notifications, applications, or other forms of proactive communication could help consumers understand when tariff costs are increasing and give them an opportunity to respond.

The interviewee also raised questions regarding DSO cost recovery. If consumers respond successfully and avoid high congestion tariffs, tariff revenues may decline even though significant network investments may still be required. This issue should therefore be considered explicitly when calibrating the mechanism.

Another practical concern is smart-meter reliability. Dynamic settlement depends on accurate time-specific consumption data. Missing meter data can be difficult to reconstruct and may result in inaccurate tariff charges, making data quality an important implementation requirement.

The interviewee was cautious about removing grid-tariff billing completely from the supplier relationship. Although direct DSO billing may reduce supplier implementation costs, separating the network charge could also influence how consumers perceive the tariff and its urgency.

Overall, the concept of dynamic grid tariffs was considered promising, but substantial attention is required for consumer information, flexibility potential, affordability, data reliability, and the interaction with existing electricity contracts.

B.11 EddyGrid

The interview focused primarily on the role that aggregators could play in responding to dynamic grid tariffs and managing flexibility for both large and small electricity consumers. For large consumers, variable grid tariffs were considered potentially useful because an aggregator can incorporate these tariff differences into its optimisation strategy. The interviewee noted that the value of such optimisation also depends on developments in other electricity markets. Since the connection of Picasso, the spread between imbalance prices has decreased, which affects the available revenue opportunities for aggregators.

For small-scale consumers, a similar aggregation role is considered technically possible, but automation is essential. Individual consumers cannot realistically be expected to continuously respond to changing grid tariffs themselves. Software that automatically coordinates flexible assets could therefore provide

substantial value for households. EddyGrid could potentially act as an intermediary by optimising household flexibility on behalf of consumers.

Although such a structure is theoretically feasible, the interviewee emphasised that the reliability of the underlying technical systems represents an important practical risk. Large-scale residential aggregation requires many different systems to communicate correctly and continuously. Failures in communication, software, or system integration could create financial risks for consumers when their assets fail to respond as expected. A robust and highly automated infrastructure would therefore be required before such a mechanism could be implemented at scale.

Aggregation may also provide opportunities for managing financial risks. Some aggregators currently allow customers to transfer or buy off part of their imbalance risk, while others leave this risk with the customer. Within a sufficiently large aggregation, positive and negative deviations may partly offset each other, potentially reducing portfolio-level imbalance exposure. Such risk management becomes more feasible when a large number of assets can be coordinated automatically. The use of a Home Energy Management System (HEMS) was therefore considered particularly promising for small-scale consumer flexibility.

An important institutional question concerns responsibility for the operation and maintenance of this infrastructure. Large-scale aggregation requires investment in software, communication systems, interfaces between different technologies, and continuous maintenance. The interviewee questioned which actor should ultimately be responsible for ensuring that these systems continue to function reliably. Under current conditions, implementation at large scale was considered difficult because the required communication and integration infrastructure is not yet sufficiently robust.

Capacity-based arrangements were also discussed. A subscription structure could potentially be managed by an aggregator, particularly when a hard capacity limit can be enforced. Capacity Steering Contracts (CSC) provide another possible approach because they allow the coordinating party to control or limit capacity use under predefined conditions. Such mechanisms may therefore provide aggregators with greater certainty over the flexibility available during congestion periods than a structure that relies exclusively on voluntary consumer response to price signals.

C Consumer interview takeaways

The consumer interviews were intended to provide insight into the practical experiences of households participating in Stedin's EmPower pilot. Four consumers participated in the interviews. Their experiences provide indicative insights rather than a representative account of all participating households.

The interviews indicated that households' ability and willingness to respond to dynamic grid tariffs depend strongly on their daily routines. On days with sufficient time and flexibility, activities such as cooking and washing can be shifted in response to the tariff signal. On busier days, however, responding to the tariff receives considerably less attention. Because many adjustments require manual action, active demand response depends strongly on the time and attention available within households.

The interviews suggested that the relative pattern of tariff levels was more relevant to consumers than the exact financial value of the tariff. High- and low-tariff periods therefore provided clearer guidance for behavioural decisions than small differences in the precise tariff level. Reported responses included adjusting heat-pump operation to reduce consumption during peak periods. These experiences suggest that consumers can respond to dynamic tariffs when the tariff pattern is sufficiently clear and flexible appliances can be scheduled accordingly.

Comfort and existing household routines were identified as important limitations to flexibility. Not all electricity consumption can or will be shifted purely in response to tariff signals. Consumers are unlikely to continuously adapt their activities throughout the day, particularly when doing so interferes with normal routines or requires substantial attention. The interviews therefore indicate practical limits to the amount of manual flexibility that can reasonably be expected from households.

Technical reliability also affects the practical use of flexibility. Reported experiences included problems with the Homey application used to monitor and control connected devices. Such technical failures can reduce consumers' ability to observe consumption and respond to tariff signals. Reliable automation and communication systems are therefore important conditions for translating dynamic grid tariffs into actual consumer response.

Financial uncertainty should be interpreted in the context of the cost cap provided by Stedin to participants in the EmPower pilot. This protection limited the financial risk faced by the interviewed consumers. Consequently, their experiences cannot establish whether unrestricted dynamic tariff exposure would create concerns about financial risk. The protection provided within the pilot may also have influenced their willingness to participate and respond to tariff signals.

The timing of tariff information emerged as an important consideration in the interviews. Day-ahead publication was viewed as necessary for manually shifting household activities within a day, while a shorter time horizon would make this considerably more difficult. A longer horizon of approximately one week could provide additional value by allowing households to incorporate expected tariff patterns into their weekly planning. The practical usefulness of tariff information therefore depends not only on its accuracy, but also on whether it is available sufficiently far in advance for consumers to act upon it.

The interviews also indicated that participation in the pilot was not motivated solely by financial benefits. Reported motivations included contributing to improvements in the electricity system and participating in innovative developments. This introduces a potential selection effect, as voluntary pilot participants may be more interested in energy flexibility and more willing to adjust their behaviour than the average electricity consumer.

Overall, the interviews highlight four main consumer-related considerations for dynamic grid tariffs: limited willingness to perform continuous manual demand response, the importance of comfort and existing routines, the need for reliable automation and sufficiently early tariff information, and the influence of financial protection on consumer acceptance.

D ADT blocks data

Table 36: Monthly ADT tariff categories and corresponding tariff levels in the base-case simulation.

Month	Tariff category	Tariff [EUR/kWh]	Hours
January	Off-peak	0.050000	341
	Normal	0.053333	155
	Peak	0.108718	248
February	Off-peak	0.050000	252
	Normal	0.051708	196
	Peak	0.103934	224
March	Off-peak	0.050000	341
	Normal	0.052071	155
	Peak	0.155068	248
April	Off-peak	0.050000	360
	Normal	0.051394	120
	Peak	0.097087	240
May	Off-peak	0.050000	372
	Normal	0.050885	124
	Peak	0.075012	248
June	Off-peak	0.050000	360
	Normal	0.051451	120
	Peak	0.081966	240
July	Peak	0.054041	744
August	Off-peak	0.050000	465
	Normal	0.050304	31
	Peak	0.057427	248
September	Peak	0.050936	720
October	Peak	0.055669	744
November	Off-peak	0.050000	390
	Normal	0.051124	90
	Peak	0.087092	240
December	Off-peak	0.050000	341
	Normal	0.051993	155
	Peak	0.094441	248

Hours represent the total number of hourly observations assigned to each category within the month. Each month–category combination contains exactly one unique tariff value: its minimum and maximum are identical, and its tariff range is zero. Category names reproduce the model output. In months containing only one category, the label Peak does not imply high congestion throughout the month.

E Calibration of subscription sizes

The subscription sizes for the volumetric and capacity-based designs were calibrated based on the observed consumption characteristics of the representative consumer profiles. The objective of this calibration was to define a limited number of subscription classes that cover normal household demand while maintaining exposure to the dynamic tariff during relatively high-demand periods.
For both subscription designs, the calibration was performed before the corresponding subscription prices were determined. This separates the technical determination of subscription size from the financial calibration of subscription prices.

E.1 Volumetric subscription sizes

The volumetric subscription levels were determined based on monthly net electricity import. For each of the eight consumer profiles, hourly net import was aggregated to monthly electricity volumes. This resulted in twelve monthly observations per consumer profile.
For each profile, descriptive statistics of monthly net import were calculated, including the mean, median, 75th percentile, 90th percentile, and maximum monthly consumption. The 75th percentile was used as the main reference point for identifying normal but relatively high monthly consumption. This percentile was selected because it covers the majority of normal monthly demand while still allowing approximately the highest-consumption months to exceed the subscribed volume and remain exposed to the dynamic tariff.
The 75th percentile values showed three broad groups of consumer profiles:

- low-volume profiles, with monthly consumption around 200 kWh;
- medium-volume profiles, with monthly consumption around 400–500 kWh;
- high-volume profiles, with monthly consumption around 650–750 kWh.

Based on these observed consumption clusters, three rounded subscription levels were selected:

- Small: 200 kWh/month;
- Medium: 450 kWh/month;
- Large: 650 kWh/month.

The selected values therefore represent simplified subscription classes derived from the empirical distribution of monthly electricity demand rather than profile-specific subscription limits.

E.2 Calibration of volumetric subscription sizes

Based on the analysis of monthly electricity consumption, three volumetric subscription levels were selected. The final configuration consists of a Small subscription of 200 kWh/month, a Medium subscription of 450 kWh/month, and a Large subscription of 650 kWh/month. Consumer profiles were assigned to these subscription levels based on their monthly consumption characteristics, while maintaining sufficient exposure to the dynamic tariff during higher-consumption months.
The corresponding monthly fees were subsequently calibrated by considering both consumer cost exposure and population-weighted DSO tariff revenues. As with the capacity subscriptions, the prices do not increase proportionally with the subscribed volume. Instead, a relatively large base cost is incorporated in the Small subscription, while additional subscribed volume becomes progressively less expensive. This limits excessive fixed costs for high-consumption and asset-intensive households while maintaining a financial incentive to select a smaller subscription when possible.
The resulting subscription levels and prices are presented in Table 37.

Table 37: Selected volumetric subscription levels and monthly fees

Subscription	Subscribed volume (kWh/month)	Monthly fee (€)
Small	200	25
Medium	450	34
Large	650	40

The subscription assignment across the representative consumer profiles is shown in Table 38.

Table 38: Volumetric subscription assignment by consumer profile

Consumer profile	Subscription	Volume (kWh/month)
CP1	Small	200
CP2	Small	200
CP3	Medium	450
CP4	Medium	450
CP5	Large	650
CP6	Medium	450
CP7	Large	650
CP8	Large	650

E.3 Capacity subscription sizes

The capacity subscription levels were calibrated based on hourly grid import. For each consumer profile, the distribution of hourly import capacity was analysed using the mean, median, 75th, 90th, 95th, and 99th percentiles, together with the maximum observed load.
The percentile analysis showed that the profiles can be divided into conventional household demand, structurally higher electricity demand, and short-duration asset-driven peak demand. In particular, EV-equipped profiles showed a large difference between the 95th and 99th percentiles, indicating that relatively infrequent EV charging events create high capacity peaks. Using a high percentile directly as the subscription level would therefore protect most of these peaks and substantially reduce the dynamic tariff incentive.
For this reason, candidate capacity subscription levels were evaluated based on the share of imported electricity occurring above each capacity threshold. Capacity levels between 0.5 and 10 kW were tested. For each threshold, both the number of exceedance hours and the share of total imported electricity above the subscribed capacity were calculated.
The results showed three practically distinct capacity ranges. A 1 kW subscription covered conventional household demand, while approximately 3 kW was sufficient to cover nearly all structurally higher demand associated with the heat-pump profile. For asset-intensive profiles, a 6 kW subscription provided substantially more protected capacity while maintaining meaningful exposure to the dynamic tariff during high-capacity events such as EV charging.
The following three capacity subscription levels were therefore selected:

- Small: 1 kW;
- Medium: 3 kW;
- Large: 6 kW.

The objective was not to eliminate capacity exceedance completely. Instead, the subscription levels were selected to protect normal electricity demand while deliberately retaining dynamic tariff exposure during unusually high-capacity periods.
The subscription sizes were therefore derived from the underlying consumption distributions and were not calibrated based on the resulting consumer costs or DSO revenues. Subscription prices were determined in a subsequent calibration step, using cost exposure and cost recovery as separate evaluation considerations.

E.4 Calibration of subscription prices

After determining the subscription sizes, the corresponding subscription prices were calibrated separately. The objective was to establish a logical price progression between the subscription levels while balancing consumer cost exposure and DSO cost recovery.
First, the prices were structured such that larger subscriptions have a higher fixed monthly cost than smaller subscriptions. This preserves an economic incentive for consumers to select a lower subscription level when their electricity consumption or capacity requirements allow them to do so. The price differences between the subscription levels were kept approximately proportional to the additional volume or capacity provided, thereby avoiding disproportionate price differences between subscription classes.
The initial subscription prices were subsequently evaluated using the model outcomes for consumer cost exposure and DSO cost recovery. Consumer cost exposure was assessed by comparing the resulting tariff costs for each consumer profile with the static reference tariff. At the same time, the population-weighted tariff revenues were compared with the revenues under the reference case to determine the revenue difference for the DSO.
The subscription prices were iteratively adjusted to balance these two objectives. Increasing subscription prices improves DSO cost recovery, but simultaneously increases the financial exposure of consumers. Conversely, lower subscription prices reduce consumer costs but may result in insufficient tariff revenues. Particular attention was therefore paid to avoiding disproportionate cost increases for individual consumer profiles while reducing the aggregate revenue difference.
The final subscription prices should therefore not be interpreted as uniquely optimal tariff levels. Instead, they represent a calibrated configuration that maintains a logical relationship between subscription size and price while providing a reasonable trade-off between consumer cost exposure and DSO cost recovery.
The selected subscription prices result in a small positive revenue difference for the DSO in the case without flexibility activation. This was considered acceptable because the subscription mechanism is explicitly designed to incentivise consumers to respond to the dynamic tariff. When flexibility is activated, consumers can reduce their tariff costs by shifting flexible demand away from periods in which their subscribed capacity is exceeded and dynamic tariffs are high. Consequently, successful flexibility activation simultaneously reduces consumer cost exposure and tariff revenues for the DSO. The initial tariff configuration was therefore calibrated to achieve approximate, rather than exact, revenue neutrality before flexibility activation. A small positive revenue margin was retained to account for the expected reduction in tariff revenues resulting from flexibility responses. For example, consumer profiles containing an EV initially experience relatively high cost exposure, but also have substantial potential to reduce these costs through smart charging. This creates the intended economic incentive to use flexibility while simultaneously bringing aggregate tariff revenues closer to the reference level.

Table 39: Selected capacity subscription levels and monthly fees

Subscription	**Subscribed capacity (kW)**	**Monthly fee (€)**
Small	1	26
Medium	3	30
Large	6	40

The final capacity subscription structure is presented in Table 39. The price structure deliberately does not increase proportionally with subscribed capacity. A relatively large base subscription fee is applied to all subscription levels, while the additional cost of obtaining a higher capacity subscription increases more gradually. This prevents asset-intensive consumer profiles from facing disproportionately high fixed costs, while retaining a financial incentive to select a smaller subscription when a higher subscribed capacity is not required.
The subscription prices were calibrated by jointly considering consumer cost exposure and population-weighted DSO tariff revenues. The selected configuration results in approximate revenue neutrality while avoiding excessive cost increases for individual consumer profiles. Exact revenue neutrality was not imposed, as flexibility responses can subsequently reduce both consumer tariff costs and DSO tariff revenues.

Table 40: Capacity subscription assignment by consumer profile

Consumer profile	**Subscription**	**Capacity (kW)**
CP1	Small	1
CP2	Small	1
CP3	Large	6
CP4	Medium	3
CP5	Large	6
CP6	Large	6
CP7	Large	6
CP8	Large	6

F Consumer cost exposure tables

Table 41: Consumer cost exposure under the static tariff design

Profile	Tariff costs (€)	Total costs (€)	Difference (€)
CP1	353.03	1035.01	0.00
CP2	353.03	660.34	0.00
CP3	353.03	1867.19	0.00
CP4	353.03	1612.15	0.00
CP5	353.03	2444.33	0.00
CP6	353.03	1492.43	0.00
CP7	353.03	2056.82	0.00
CP8	353.03	1610.18	0.00

Table 42: Consumer cost exposure under the EmPower design

Profile	Tariff costs (€)	Total costs (€)	Difference (€)	Difference (%)
CP1	178.48	860.46	-174.55	-49.44
CP2	-4.30	303.02	-357.33	-101.22
CP3	352.97	1867.13	-0.01	-0.02
CP4	336.04	1595.16	-16.99	-4.81
CP5	510.53	2601.83	157.50	44.61
CP6	170.19	1309.59	-182.84	-51.79
CP7	327.75	2031.54	-25.28	-7.16
CP8	153.43	1456.02	-199.60	-56.54

Table 43: Consumer cost exposure under the Targeted EmPower design

Profile	Tariff costs (€)	Total costs (€)	Difference (€)	Difference (%)
CP1	128.21	810.19	-224.86	-63.69
CP2	-54.57	252.75	-407.64	-115.45
CP3	302.70	1816.86	-50.37	-14.27
CP4	285.77	1544.89	-67.30	-19.06
CP5	460.26	2551.56	107.19	30.36
CP6	119.92	1259.33	-233.15	-66.03
CP7	277.48	1981.27	-75.59	-21.41
CP8	103.16	1405.75	-249.91	-70.78

Table 44: Consumer cost exposure under the EmPower Flex Volumetric design

Profile	Tariff costs (€)	Total costs (€)	Difference (€)	Difference (%)
CP1	316.69	998.67	-36.34	-10.29
CP2	182.50	489.81	-170.53	-48.31
CP3	426.38	1940.54	73.35	20.78
CP4	489.90	1749.02	136.87	38.77
CP5	574.92	2666.22	221.89	62.85
CP6	292.27	1431.68	-60.76	-17.21
CP7	436.05	2139.84	83.02	23.52
CP8	313.69	1642.34	-39.34	-11.14

Table 45: Consumer cost exposure under the EmPower Flex Capacity design

Profile	Tariff costs (€)	Total costs (€)	Difference (€)	Difference (%)
CP1	312.00	993.98	-41.03	-11.62
CP2	193.16	500.48	-159.87	-45.28
CP3	561.92	2076.08	208.89	59.17
CP4	361.05	1620.17	8.02	2.27
CP5	567.70	2659.00	214.67	60.81
CP6	442.99	1582.39	89.96	25.48
CP7	453.26	2157.05	100.23	28.39
CP8	274.01	1625.52	-79.02	-22.38

Table 46: Consumer cost exposure under the Ex-post Bonus design

Profile	Net tariff costs (€)	Total costs (€)	Difference (€)	Difference (%)
CP1	241.80	923.78	-111.23	-31.51
CP2	4.28	311.60	-348.75	-98.79
CP3	566.29	2080.45	213.26	60.41
CP4	509.36	1768.48	156.33	44.28
CP5	833.85	2925.15	480.82	136.20
CP6	328.74	1468.14	-24.29	-6.88
CP7	592.02	2295.81	238.99	67.70
CP8	418.87	1699.29	65.84	18.65

Table 47: Consumer cost exposure under the Adaptive Dynamic Tariff design

Profile	Tariff costs (€)	Total costs (€)	Difference (€)	Difference (%)
CP1	173.07	855.05	-179.96	-50.98
CP2	-25.36	281.95	-378.39	-107.18
CP3	368.55	1882.71	15.52	4.40
CP4	323.84	1582.96	-29.19	-8.27
CP5	519.32	2610.62	166.29	47.10
CP6	170.12	1309.53	-182.91	-51.81
CP7	320.89	2024.68	-32.14	-9.10
CP8	254.96	1524.41	-98.07	-27.78

G Quantitative assessment tables

Table 48: Summary of quantitative evaluation indicators

Indicator	Static	Full RTP	Targeted	Flex Vol.	Flex Cap.	Ex-post	ADT
Consumer cost exposure Mean [€/year]	0.00	-99.89	-150.20	+26.02	+42.73	+83.87	-89.86
Consumer cost exposure Range [€/year]	[0.00, 0.00]	[-357.33, +157.50]	[-407.64, +107.19]	[-170.53, +221.89]	[-159.87, +214.67]	[-348.75, +480.82]	[-378.39, +166.29]
Cost recovery ΔR, € million/year	0.00	-295.20	-404.27	-6.10	+19.81	0.00	-295.26
Tariff volatility CoV	0.00	0.60	0.60	0.60	0.60	0.33	0.37
Tariff reflectiveness Pearson r	–	1.00	1.00	1.00	1.00	1.00	0.62

Table 49: Summary of economic incentives and price-signal interaction

Indicator	Static	Full RTP	Targeted	Flex Vol.	Flex Cap.	Ex-post	ADT
Flexibility benefit Mean [€/year]	162.08	196.60	196.60	171.25	194.07	201.86	178.35
Flexibility benefit Range [€/year]	[11.30, 462.49]	[5.54, 575.51]	[5.54, 575.51]	[6.00, 498.00]	[5.54, 531.53]	[5.54, 596.52]	[5.35, 500.27]
Congestion incentive Mean [€/year]	0.00	50.80	50.80	31.75	61.25	50.51	24.56
Congestion incentive Range [€/year]	[0.00, 0.00]	[-2.24, 174.32]	[-2.24, 174.32]	[-2.00, 122.00]	[-2.24, 179.25]	[-2.24, 173.15]	[-2.08, 65.93]
Asset incentive Mean [ΔT^{eff}, €/kWh]	0.00	-0.04	-0.06	-0.01	-0.00	-0.01	-0.04
Asset incentive Range [€/kWh]	[0.00, 0.00]	[-0.24, +0.02]	[-0.28, +0.01]	[-0.12, +0.03]	[-0.11, +0.04]	[-0.24, +0.06]	[-0.26, +0.02]
Price-signal interaction Aligned / conflicting [%]	–	52.77 / 47.23	52.77 / 47.23	52.77 / 47.23	52.77 / 47.23	52.77 / 47.23	47.65 / 52.35

H Data: economic incentives criterion

Table 50: Change in effective grid-tariff burden relative to the Static tariff by household profile and mechanism [€/kWh]. Negative values indicate a lower effective tariff burden; positive values indicate a higher burden.

Profile	Static	Full RTP	Targeted	Flex Vol.	Flex Cap.	Ex-post	ADT
CP1	0.00000	-0.06807	-0.08768	-0.01417	-0.01600	-0.04338	-0.07018
CP2	0.00000	-0.24318	-0.27739	-0.11605	-0.10880	-0.23734	-0.25751
CP3	0.00000	-0.00001	-0.00905	+0.01318	+0.03754	+0.03833	+0.00279
CP4	0.00000	-0.00357	-0.01412	+0.02873	+0.00168	+0.03281	-0.00613
CP5	0.00000	+0.02029	+0.01381	+0.02858	+0.02765	+0.06193	+0.02142
CP6	0.00000	-0.04091	-0.05216	-0.01360	+0.02013	-0.00544	-0.04093
CP7	0.00000	-0.00384	-0.01148	+0.01261	+0.01522	+0.03630	-0.00488
CP8	0.00000	-0.01282	-0.02070	+0.00964	+0.00270	+0.03328	+0.00512

Table 51: Annual flexibility benefits by mechanism and asset. Tariff benefits represent savings in grid-tariff costs; total benefits include both grid-tariff and electricity-price effects. All values are expressed in euros per year. Negative values indicate an increase in costs.

Mechanism	Flexibility measure	Tariff benefit	Total benefit
Static	PV curtailment	0.00	11.30
	EV smart charging	0.00	129.11
	Heat-pump flexibility	0.00	45.40
	Battery operation	0.00	462.49
	Sum	**0.00**	**648.30**
Full EmPower	PV curtailment	-2.24	5.54
	EV smart charging	9.76	138.83
	Heat-pump flexibility	21.37	66.54
	Battery operation	174.32	575.51
	Sum	**203.21**	**786.42**
Targeted EmPower	PV curtailment	-2.24	5.54
	EV smart charging	9.76	138.83
	Heat-pump flexibility	21.37	66.54
	Battery operation	174.32	575.51
	Sum	**203.21**	**786.42**
Flex Volumetric	PV curtailment	-2.00	6.00
	EV smart charging	0.00	129.00
	Heat-pump flexibility	7.00	52.00
	Battery operation	122.00	498.00
	Sum	**127.00**	**685.00**
Flex Capacity	PV curtailment	-2.24	5.54
	EV smart charging	67.72	194.27
	Heat-pump flexibility	0.27	44.93
	Battery operation	179.25	531.53
	Sum	**245.00**	**776.27**
Ex-post Bonus	PV curtailment	-2.24	5.54
	EV smart charging	9.76	138.83
	Heat-pump flexibility	21.37	66.54
	Battery operation	173.15	596.52
	Sum	**202.04**	**807.43**
ADT	PV curtailment	-2.08	5.35
	EV smart charging	16.46	144.87
	Heat-pump flexibility	17.93	62.90
	Battery operation	65.93	500.27
	Sum	**98.24**	**713.39**

Note: Benefits compare flexible operation with the corresponding reference operation under the same tariff mechanism; they are not differences relative to the Static mechanism. Sums aggregate the separately calculated asset-specific benefits and do not necessarily represent the jointly achievable benefit for a household operating all four assets. Values are reproduced at the precision reported in the individual results tables.

Table 52: Detailed comparison of CP7 without a battery and CP8 with optimised battery operation under Flex Capacity. Both profiles have identical underlying demand and PV profiles, a subscribed capacity of 6 kW, and an annual subscription fee of EUR 480.

(a) Capacity exceedance and household import

Indicator	CP7	CP8	Reduction
Exceedance duration: all hours [h]	265	265	0
Exceedance duration: during congestion [h]	53	53	0
Exceedance energy: all hours [kWh]	1493.21	856.68	636.52
Exceedance energy: during congestion [kWh]	301.83	148.33	153.50
Exceedance charges: all hours [EUR]	87.57	49.22	38.35
Exceedance charges: during congestion [EUR]	28.00	13.80	14.20
Maximum import: all hours [kW]	13.72	13.71	0.01
Maximum import: during congestion [kW]	13.34	11.89	1.44

(b) Annual costs and battery benefits

Cost component [EUR/year]	CP7	CP8	Saving
Subscription costs	480.00	480.00	0.00
Capacity-exceedance charges	87.57	49.22	38.35
Grid-tariff export component	−114.31	−255.20	140.89
Total grid-tariff costs	**453.26**	**274.01**	**179.25**
Electricity import costs	1810.32	1705.90	104.42
Other export costs/revenues	−106.53	−354.40	247.87
Total electricity costs	**2157.05**	**1625.52**	**531.53**

Reductions and savings are calculated as CP7 minus CP8. Congestion refers to consumption congestion in the exogenous network signal. Exceedance energy is the time integral of household import above the subscribed capacity. Negative cost entries represent net revenues. Total grid-tariff costs include the subscription, capacity-exceedance charges, and grid-tariff export component. Total electricity costs include total grid-tariff costs, electricity import costs, and other export costs/revenues. Differences and totals are calculated before rounding.

I Qualitative assessment tables

The tables in this appendix provide the underlying coding used for the qualitative evaluation in Chapter 9. For simplicity of implementation, little additional burdens, and delineation of actor roles, a value of 1 indicates that an additional requirement or burden is present. A lower score is therefore more favourable. For clear purpose and non-discrimination, a value of 1 indicates that the corresponding characteristic is satisfied, meaning that a higher score is more favourable.

A characteristic is coded only when it follows from the conceptual specification of the mechanism. Optional supporting arrangements are not counted unless they are necessary for the mechanism to function.

I.1 Simplicity of implementation

I.1.1 Assessment table

Table 53: Assessment of simplicity of implementation

Mechanism	Metering	Billing	Reg./sub.	Comm./control	Data exchange	Score
Static	0	0	0	0	0	0/5 – Good
Full RTP	0	1	0	0	1	2/5 – Moderate
Targeted RTP	1	1	1	0	1	4/5 – Poor
Flex Vol.	0	1	1	1	1	4/5 – Poor
Flex Cap.	0	1	1	1	1	4/5 – Poor
Ex-post	0	1	0	1	1	3/5 – Moderate
ADT	0	1	0	0	1	2/5 – Moderate

I.1.2 Assessment explanation

Static tariff. The static tariff represents the existing reference structure and therefore requires no additional metering, billing logic, registration system, communication infrastructure, or data exchange.

Full RTP. Full RTP does not require separate asset measurement or registration because all household consumption is exposed to the same dynamic tariff. However, suppliers must be able to process time-varying grid tariffs in their billing systems, while tariff information must be exchanged between the DSO and the relevant market actors. No new communication or control infrastructure is assumed to be inherently required.

Targeted RTP. Targeted RTP requires flexible assets to be identified, registered, and measured separately because only these assets are exposed to the dynamic tariff. Billing systems must therefore distinguish between flexible-asset consumption and other household demand, which also requires additional data exchange between the actors responsible for measurement, tariff determination, and billing.

Flex Volumetric. The volumetric subscription requires additional billing logic to combine a fixed subscription fee with dynamic pricing once the subscribed volume is exceeded. A subscription registration system and additional exchange of subscription, consumption, and tariff information are therefore required. In addition, a new communication and monitoring infrastructure is required to continuously track the subscribed volume, determine when dynamic exposure becomes applicable, and communicate the relevant information to consumers or automated energy-management systems.
Flex Capacity. The capacity subscription similarly requires additional billing logic, subscription administration, and exchange of information regarding the subscribed capacity and tariff exposure. In addition, a communication and monitoring infrastructure is required to continuously compare household demand with the subscribed capacity, determine when dynamic exposure applies during congestion periods, and communicate these signals to consumers or automated energy-management systems. Separate asset measurement is not required because the capacity threshold applies to total household demand.

Ex-post Bonus. The Ex-post Bonus requires new settlement logic to calculate the financial correction after the settlement period. In addition, a technical communication and transaction process is required to apply the correction to consumers, either through a separate payment or through the subsequent billing process. This also requires additional data exchange between the party calculating the correction and the party responsible for executing and communicating the settlement. No separate asset measurement or registration system is required.
ADT. ADT requires suppliers to process periodically updated tariff periods and requires the DSO to communicate these tariff structures to the relevant market actors. It does not require separate asset measurement, a registration system, or new control infrastructure.

I.2 Additional burdens

I.2.1 Assessment table

Table 54: Assessment of additional recurring burdens

Mechanism	Consumer	Billing	Admin.	Monitoring	Coordination	Score
Static	0	0	0	0	0	0/5 – Good
Full RTP	0	1	0	1	0	2/5 – Moderate
Targeted RTP	0	1	1	1	1	4/5 – Poor
Flex Vol.	0	1	1	1	0	3/5 – Moderate
Flex Cap.	0	1	1	1	0	3/5 – Moderate
Ex-post	0	1	0	0	1	2/5 – Moderate
ADT	0	1	0	1	0	2/5 – Moderate

I.2.2 Assessment explanation

Static tariff. The static tariff does not introduce additional recurring activities compared with the existing tariff structure and therefore receives no additional burden scores.

Full RTP. Full RTP requires suppliers to continuously process dynamic tariff values in billing and requires the DSO to monitor network conditions and determine the corresponding congestion-based tariffs. These activities recur throughout operation. No recurring subscription administration or additional inter-actor coordination arrangement is required beyond the tariff-information process itself.

Targeted RTP. Targeted RTP introduces several recurring activities. Asset-specific consumption must continuously be processed in billing, registrations of participating flexible assets must be maintained, and the relevant asset consumption must be monitored. In addition, ongoing coordination is required between the actors responsible for asset registration, measurement, tariff determination, and billing.

Flex Volumetric. The volumetric subscription requires recurring billing of the subscription and dynamic tariff exposure, continued administration of subscription levels, and monitoring of cumulative consumption to determine when the subscribed volume has been exceeded. No additional recurring consumer action or separate inter-actor coordination arrangement is assumed to be necessary.

Flex Capacity. The capacity subscription requires recurring billing, administration of subscribed capacity levels, and monitoring of household demand to determine whether the subscribed capacity is exceeded during congestion periods. As with the volumetric mechanism, no recurring manual consumer action or additional coordination arrangement is assumed to be inherently required.

Ex-post Bonus. The Ex-post Bonus introduces an additional recurring settlement activity because the ex-post correction must be calculated and incorporated into consumer billing after each settlement period. This also requires coordination between the actor determining the correction and the actor responsible for applying it. No subscription administration or additional continuous monitoring requirement is introduced beyond that already required for the underlying tariff.

ADT. ADT requires recurring processing of updated tariff periods by suppliers and periodic monitoring and analysis of local congestion patterns by the DSO in order to determine future tariff periods. It

does not require subscription administration or additional recurring coordination arrangements beyond the normal tariff-information process.

I.3 Clear purpose

I.3.1 Assessment table

Table 55: Assessment of clear purpose of the tariff mechanism

Mechanism	Tariff cause	Behaviour	Financial effect	Score	Assessment
Static	0	0	1	1/3	Poor
Full RTP	1	1	1	3/3	Good
Targeted RTP	1	1	1	3/3	Good
Flex Vol.	1	0	1	2/3	Moderate
Flex Cap.	1	1	1	3/3	Good
Ex-post	1	1	0	2/3	Moderate
ADT	1	1	1	3/3	Good

I.3.2 Assessment explanation

Static tariff. The static tariff has a direct and predictable financial consequence, since the tariff rule determines the final payment without additional calculations. However, the tariff does not vary with congestion and therefore does not provide an identifiable congestion-related trigger or behavioural response through which consumers can reduce grid-tariff costs.

Full RTP. Under Full RTP, the relationship between grid conditions, consumer behaviour, and tariff costs is direct. Higher local congestion results in a higher tariff, consumers can reduce costs by shifting or reducing consumption during these periods, and the resulting financial consequence follows directly from the applicable tariff.

Targeted RTP. Targeted RTP retains the same direct congestion-related logic for the flexible assets to which the tariff applies. The cause of the tariff change is identifiable, the desired response of the flexible asset is clear, and the resulting financial consequence follows directly from the tariff applied to that asset.

Flex Volumetric. The tariff exposure rule is identifiable: consumption above the subscribed monthly volume becomes exposed to the dynamic tariff. The resulting financial consequence also follows directly from this rule. However, the desired congestion-reducing behaviour is less unambiguous because reducing total monthly electricity volume is only indirectly related to reducing coincident demand during congestion periods.

Flex Capacity. Flex Capacity provides a clear relationship between network-relevant behaviour and financial consequences. Consumers know that exceeding their subscribed capacity during congestion periods results in dynamic tariff exposure and can reduce this exposure by remaining below the subscribed capacity during those periods. The final financial consequence follows directly from this rule.

Ex-post Bonus. The underlying congestion signal and desired behavioural response remain clear during operation: higher congestion results in a higher tariff and consumers can reduce costs by shifting consumption. However, the final financial consequence is subsequently modified by an ex-post correction, meaning that the final tariff payment does not follow solely from the tariff rule faced during consumption.

ADT. ADT provides predefined higher- and lower-tariff periods based on expected local congestion patterns. Consumers can identify when higher tariffs apply, can reduce costs by shifting consumption away from these periods, and the financial consequence follows directly from the communicated tariff structure.

I.4 Delineation of actor roles

I.4.1 Assessment table

Table 56: Assessment of delineation of actor roles

Mechanism	New role	New resp.	Delineation	Coordination	New agreements	Score
Static	0	0	0	0	0	0/5 – Good
Full RTP	0	1	0	1	0	2/5 – Moderate
Targeted RTP	0	1	1	1	0	3/5 – Moderate
Flex Vol.	0	1	1	1	0	3/5 – Moderate
Flex Cap.	0	1	1	1	0	3/5 – Moderate
Ex-post	0	1	1	1	0	3/5 – Moderate
ADT	0	1	0	1	0	2/5 – Moderate

I.4.2 Assessment explanation

Static tariff. The static tariff operates within the existing allocation of responsibilities between the DSO, suppliers, and consumers and therefore does not introduce additional role-allocation requirements.

Full RTP. Full RTP does not require a new market actor, but it does create additional responsibilities for existing actors. The DSO must determine and communicate frequently changing local tariffs, while suppliers must process these tariffs in their billing and customer-facing systems. This requires more intensive recurring coordination between the DSO and suppliers than under the static tariff. The general division of responsibilities remains identifiable, so no additional role delineation or new institutional agreement is assumed to be required.

Targeted RTP. Targeted RTP introduces additional responsibilities related to the registration, measurement, and processing of flexible assets. Because these tasks could be performed by suppliers or another coordinating actor, the exact allocation of responsibilities requires further delineation. Ongoing coordination is also needed between the DSO, the party administering the assets, and the party responsible for billing. No fundamentally new market role or new institutional agreement is assumed to be necessary.

Flex Volumetric. The volumetric subscription introduces additional responsibilities for subscription registration, administration, and settlement. The allocation of these responsibilities between the DSO, supplier, and potentially an intermediary requires further specification, while recurring coordination is required to connect subscription information with tariff determination and billing. No new actor role is inherently required.

Flex Capacity. The capacity subscription similarly introduces new responsibilities related to registering and administering subscribed capacity levels and processing capacity exceedance. The precise allocation of these activities between the DSO, supplier, and potentially an intermediary requires further delineation and coordination. However, these activities can in principle be assigned to existing market actors.

Ex-post Bonus. The Ex-post Bonus introduces an additional responsibility for calculating and distributing the ex-post financial correction. Since this responsibility could be allocated to the DSO, supplier, or another designated actor, further delineation is required. Coordination is also necessary between the actor calculating the correction and the actor applying it to consumer settlement. No new actor role is inherently required.

ADT. ADT does not introduce a new market actor, but existing actors receive additional responsibilities. The DSO must periodically determine locally applicable tariff periods, while suppliers must receive, implement, and communicate the updated tariff structure. This requires intensified coordination between the DSO and suppliers. The general allocation of responsibilities nevertheless remains sufficiently clear and does not require the introduction of a new role or institutional agreement.

I.5 Non-discrimination

I.5.1 Assessment table

Table 57: Assessment of non-discrimination

Mechanism	Equal treatment	Location	Network-based	Score	Assessment
Static	1	1	1	3/3	Good
Full RTP	1	0	1	2/3	Moderate
Targeted RTP	0	0	1	1/3	Poor
Flex Vol.	1	0	1	2/3	Moderate
Flex Cap.	1	0	1	2/3	Moderate
Ex-post	1	0	1	2/3	Moderate
ADT	1	0	1	2/3	Moderate

I.5.2 Assessment explanation

Static tariff. The static tariff applies the same tariff principles to comparable consumers and does not differentiate according to asset type, purpose of electricity use, or local congestion conditions. It is therefore location-neutral and does not introduce additional differentiation unrelated to electricity-network use.

Full RTP. Full RTP treats comparable electricity use within the same tariff area equally and does not distinguish between asset types or the purpose for which electricity is consumed. However, the tariff is determined using local network conditions. Consequently, otherwise comparable consumers connected at different locations can face different tariff levels. The differentiation itself remains based on network conditions rather than personal consumer characteristics.

Targeted RTP. Targeted RTP introduces two forms of differentiation. First, the underlying EmPower tariff varies according to local congestion conditions and is therefore location-dependent. Second, identical electricity consumption can receive different tariff treatment depending on whether it is associated with a registered flexible asset or with other household demand. The differentiation is nevertheless based on observable characteristics of electricity use and the congestion-management objective rather than on personal or demographic consumer characteristics.

Flex Volumetric. The volumetric subscription applies the same subscription and tariff principles to comparable consumers and does not distinguish between asset types or purposes of electricity use. However, the dynamic tariff applied above the subscribed volume remains based on local EmPower congestion conditions and is therefore location-dependent. The differentiated treatment follows from electricity-use and network-related tariff conditions rather than from personal consumer characteristics.

Flex Capacity. The capacity subscription similarly applies the same tariff logic irrespective of asset type or purpose of use. Dynamic exposure is determined by capacity exceedance and local congestion conditions. Because the underlying EmPower tariff is location-specific, comparable consumers at different locations may face different tariff levels. The remaining differentiation is based on electricity demand and network conditions.

Ex-post Bonus. The Ex-post Bonus retains the underlying locally differentiated EmPower tariff and is therefore not location-neutral. Within a location, comparable electricity use is subject to the same tariff rule irrespective of asset type or purpose. The ex-post correction does not introduce differentiation based on consumer category, while the underlying dynamic tariff remains linked to network conditions.

ADT. ADT applies the same tariff logic to consumers within the same local tariff area and does not distinguish between asset type or purpose of electricity use. However, tariff periods are determined from local congestion patterns and can therefore differ between network locations. The differentiation is based on local network conditions rather than on personal consumer characteristics.

J Consumer electricity imports table

Table 58: Annual electricity imports by consumer profile and tariff mechanism in the base-case simulation [kWh/year].

Profile	Static	Full RTP	Targeted	Flex Vol.	Flex Cap.	Ex-post	ADT
CP1	2564.24	2564.24	2564.24	2564.24	2564.24	2564.24	2564.24
CP2	1469.42	1469.42	1469.42	1469.42	1469.42	1469.42	1469.42
CP3	5564.24	5564.24	5564.24	5564.24	5564.24	5564.24	5564.24
CP4	4764.24	4764.24	4764.24	4764.24	4764.24	4764.24	4764.24
CP5	7764.24	7764.24	7764.24	7764.24	7764.24	7764.24	7764.24
CP6	4468.87	4468.87	4468.87	4468.87	4468.87	4468.87	4468.87
CP7	6583.31	6583.31	6583.31	6583.31	6583.31	6583.31	6583.31
CP8	9573.87	6377.63	6377.63	6743.77	6924.32	5971.06	6071.00

Annual imports are calculated by summing positive hourly grid imports; electricity exports are not subtracted. CP1–CP7 retain the same operating profiles across mechanisms. CP8 includes optimised battery operation, resulting in mechanism-specific import volumes. These volumes form the denominator of the effective tariff-burden indicator.

K Tariff statistics

Table 59: Descriptive statistics of the underlying hourly grid-tariff signals in the base-case simulation. Tariff values and standard deviations are expressed in EUR/kWh; the coefficient of variation (CoV) is dimensionless.

Mechanism	Mean	Std. dev.	Minimum	Maximum	CoV
Static	–	–	–	–	–
Full RTP	0.062518	0.037203	0.050000	0.377609	0.595078
Targeted RTP	0.062518	0.037203	0.050000	0.377609	0.595078
Flex Volumetric	0.062518	0.037203	0.050000	0.377609	0.595078
Flex Capacity	0.062518	0.037203	0.050000	0.377609	0.595078
Ex-post Bonus	0.112518	0.037203	0.100000	0.427609	0.330642
ADT	0.062518	0.023129	0.050000	0.155068	0.369958

Statistics use all 8,760 hourly observations with equal weight. Standard deviations use the sample definition with denominator $N - 1$, and CoV is calculated as the standard deviation divided by the mean. For Targeted RTP and the subscription mechanisms, the values describe the underlying EmPower signal rather than household-specific exposure or fixed subscription fees. Ex-post Bonus values describe the hourly tariff before the annual rebate. Static applies a fixed annual charge rather than an hourly volumetric tariff, so these statistics are not applicable; its absence of temporal tariff variation is represented as zero in the volatility comparison.