Optimising Renewable Energy Communities

Balancing the Pillars of the Energy Trilemma

by

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I. Acknowledgments

This has been a period of discovering my passion. through conversations with colleagues, clients, supervisors, family, and friends. These conversations have guided me in exploring what makes me happy daily in a working environment. The opportunity of traveling to Delft, Amsterdam, Rotterdam, and Utrecht each day, has allowed me to draw enormous inspiration from both the people and my surroundings. Having the opportunity to ask others about their experiences, their careers, and what fuels their passion has been a privilege. From reflecting on my own first steps after graduation to embracing the excitement of new adventures ahead, this journey has been shaped by those around me. And for that, I want to thank you all.

To my colleagues at Accenture, you have shown me what passion for this field truly looks like. Thank you for sharing your knowledge, for guiding me toward my own passion, and for helping me clear so many doubts about my future. Most of all, thank you for trusting me throughout the process of writing this thesis.

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Thank you all. This journey has been as much yours as it has been mine.

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II. Company Description

This thesis was written at Accenture. Accenture is a global leader in professional services, delivering innovative solutions in strategy, consulting, technology, and operations across diverse industries. During my internship at Accenture, I have been part of the Strategy and Consulting division within the Utilities team, which is part of the Resources group. This team focuses on assisting energy and utilities companies in their transition to sustainable energy systems. The Accenture Utilities team's expertise in the energy sector and commitment to sustainability have provided a solid foundation for investigating innovative solutions, such as Renewable Energy Communities (RECs), to address critical challenges like grid congestion and the energy transition. Throughout the thesis, expert judgment from Accenture's professionals and industry specialists has been integrated to enhance the validity and practical relevance of the model.

III. Summary

The energy transition in the Netherlands, characterised by the increase of renewable energy sources (RES) and the electrification of key sectors, has placed strain on the existing electricity grid. Challenges such as volatile electricity prices, curtailment of excess renewable energy, and grid congestion highlight the limitations of the current infrastructure, particularly in urban low-voltage (LV) networks. Here, transformers get congested due to limited capacity during peak hours. Expanding the grid is often infeasible due to high costs, long timelines, and spatial constraints. However, Renewable Energy Communities (RECs) have emerged as a promising solution to these challenges by optimising the use of the existing infrastructure within local contexts.

The challenge in improving affordability, sustainability and security is that the goals are contradicting, also referred to as the Energy Trilemma. Therefore, this thesis addresses the research question: "*How can Dutch urban Renewable Energy Communities be designed and operated to enhance energy affordability, sustainability, and security?"*. To answer this, a multi-objective linear programming (MO LP) model was developed using the Calliope software framework in Python. The model optimises the design and operation of RECs across three energy trilemma dimensions: affordability, sustainability, and grid security. It incorporates solar photovoltaic (PV), battery energy storage systems (BESS), and grid interactions.

The research underscores the inherent trade-offs in balancing the energy trilemma. Affordability-driven scenarios minimise costs through extensive grid reliance, increasing emissions and transformer congestion, while sustainability- and grid-security-focused scenarios emphasize self-consumption, reducing both but incurring higher costs and curtailment. Maximizing solar PV capacity cuts CO_2 emissions but leads to substantial curtailment without sufficient storage or trading. BESS mitigate imbalances by shifting energy flows in time, yet grid dependence remains unavoidable, especially in winter when PV output is low.

There is thus no universally optimal REC design, effectiveness depends on stakeholder priorities. However, key insights hold across all scenarios: Dutch urban RECs can enhance affordability, sustainability, and security with approximately 750 kW of solar PV per 200 prosumers and 200 kW MV and LV batteries for hourly balancing. Designing RECs this way, could offer a more efficient solution for mitigating urban grid congestion than defaulting to grid expansion.

Despite its contributions, the study has limitations. The model simplifies grid interactions by focusing solely on the LV grid and transformer congestion, excluding medium-voltage (MV) and high-voltage (HV) dynamics. Behavioural feedback on market dynamics, such as the impact of widespread REC adoption on electricity prices, or the diminishing business case of batteries, is also not captured. These limitations underscore the need for future research to expand the model's scope, address emerging technologies, and integrate multi-layered grid interactions that include feedback systems.

All findings of this thesis are open source. The model that was developed to answer the research questions can be accessed at:

https://github.com/Tomdebruin/MO-LP-Energy-Community-optimisation

IV. Table of contents

V. List of Figures

VI. List of Tables

VII. Abbreviations

Abbreviation	Definition
BESS	Battery Energy Storage System
BRP	Balancing Responsible Party
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
DER	Distributed Energy Resources
DSM	Demand Side Management
DSO	Distribution System Operator
ESM	Energy System Model
ETI	Energy Trilemma Index
EU	European Union
EV	Electric Vehicle
GSA	Global Sensitivity Analysis
LP	Linear Programming
LV	Low Voltage
MGA	Modelling to Generate Alternatives
MO	Multi-Objective
MO LP	Multi-Objective Linear Programming
MV	Mid Voltage
OAT	One-at-a-Time
OPEX	Operational Expenditures
PCA	Principal Component Analysis
PV	Solar Photovoltaic Systems
REC	Renewable Energy Community
RES	Renewable Energy Source
TCF	Transformer Congestion Factor
TCI	Transformer Congestion Indicator
TSO	Transmission System Operator
V2G	Vehicle-to-Grid

1. Introduction

The introduction section of this thesis provides a structured overview of the problem statement, research objective, and alignment with the Complex Systems Engineering and Management (CoSEM) program. Lastly, we give the research outline.

1.1. Problem Statement

The Dutch efforts towards environmental sustainability and climate change mitigation, are accelerating the shift from fossil fuels to renewable energy sources (RES), also known as the ‘energy transition’ (Tweede Kamer der Staten Generaal, 2024). Electrification of sectors such as transport, heating, and industry is central to this transition, as it enables such uses of energy, traditionally served by fossil fuels, to be met via cleaner, renewable electrical energy. However, this shift brings significant challenges to the existing electricity grid, which was not designed to sustain these large, dispersed and less predictable additional loads (Tweede Kamer der Staten-Generaal, 2023).

The rapid adoption of decentralized energy resources (DERs) like solar photovoltaic (PV), places additional strain on the grid. This strain is particularly evident in urban areas, where limited transformer capacity in the distribution network restricts the ability to handle increasing demand. Grid congestion, defined as the overloading of network components like transmission cables and transformers, leads to inefficiencies, higher operational costs, and rising electricity prices (Hennig et al., 2023; Tweede Kamer der Staten-Generaal, 2023).

This problem is particularly severe in densely populated urban areas and regions with large-scale PV installations, as the bidirectional energy flows from DERs make load management more complex. If unresolved, grid congestion risks delaying the energy transition by curtailing renewable energy generation and causing unpredictable price spikes (Tweede Kamer der Staten-Generaal, 2023).

Mid Voltage (MV) congestion is portrayed in Figure 1 to give context to the present problems. According to Rijksoverheid (2024), if no action is taken, these issues are projected to affect 1.5 million small-scale consumers on the Low Voltage (LV) grid by 2030. This underscores the urgency of addressing grid congestion and accommodating the growing adoption of DERs (Rijksoverheid, 2024).

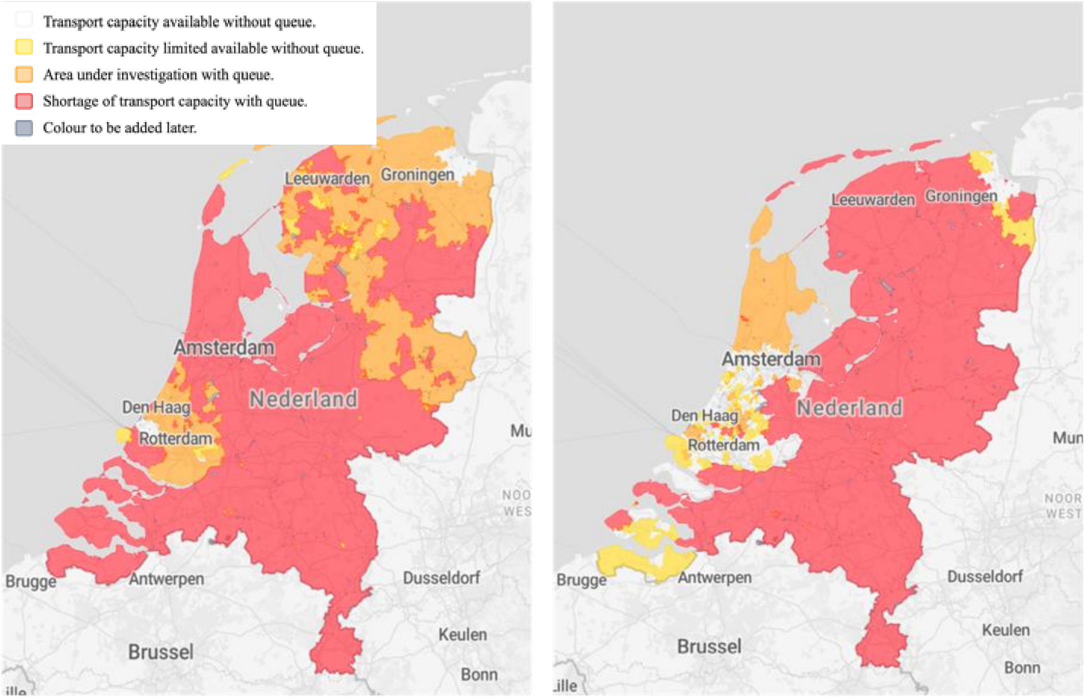

Figure 1: Dutch consumption (left) and feed-in (right) congestion in 2024 (TenneT, 2024).

We observe that the present energy landscape in the Netherlands is thus faced with the "Energy Trilemma," where energy systems must balance three competing objectives: affordability, environmental sustainability, and security of supply (Marti & Puertas, 2022; Song et al., 2017). Affordability is threatened when grid congestion forces Distribution System Operators (DSOs) to resort to expensive interventions to maintain stability. Environmental sustainability is undermined by the curtailment of renewable energy, which reduces its contribution to the energy mix and slows decarbonization efforts. Lastly, the security of supply is compromised when transformers reach their capacity limits, creating bottlenecks that hinder the grid's ability to serve increasing and fluctuating demand (Backe et al., 2022).

While expanding and reinforcing grid infrastructure may seem like a straightforward solution, these measures face significant barriers, including high costs, long implementation timelines, and spatial constraints in densely populated areas (Tweede Kamer der Staten Generaal, 2024). Moreover, in densely populated urban areas, spatial limitations further hinder the expansion of grid infrastructure. Addressing these challenges requires innovative operational strategies and efficiency measures to ensure the grid can meet growing electricity demands without compromising the energy transition.

1.2. Research Objective

One promising approach to mitigate grid congestion and optimise the use of existing infrastructure is to enhance energy system flexibility (Crowley et al., 2023; Lampropoulos et al., 2019; Ponnaganti et al., 2023; Reijnders et al., 2020; Voulis et al., 2017). Energy flexibility refers to the ability of the energy system to adapt dynamically to fluctuations in supply and demand, enabling more efficient use of assets like transformers while reducing strain on infrastructure

The European Union and Dutch policymakers have identified Renewable Energy Communities (RECs) as a promising way to increase flexibility (DIRECTIVE (EU) 2019/ 944, 2019; Tweede Kamer der Staten-Generaal, 2023). RECs enable the integration of storage technologies and smarter operational strategies, allowing local generation and consumption of renewable energy to be maximized. This reduces reliance on the centralized grid and alleviates pressure on transformers in constrained areas (Backe et al., 2022; Crowley et al., 2023; Lampropoulos et al., 2019; Reijnders et al., 2020).

Integrating Renewable Energy Communities (RECs) into existing energy grids involves complex interactions between local energy generation, storage, and consumption. To optimise the design and operation of RECs within the framework of the energy trilemma, modelling serves as a critical tool. It offers a structured approach to simulate and analyse how various design and operational strategies can simultaneously impact affordability, sustainability, and energy security (Awad & Gül, 2018; Finke et al., 2024; Garavaso et al., 2021; Pfenninger & Pickering, 2018; Secchi et al., 2021; Stegen et al., 2024). By capturing the dynamic behaviour of energy systems and simulating multiple scenarios, modelling enables policymakers and stakeholders to evaluate trade-offs and synergies between the three dimensions of the energy trilemma.

Doing so, this study will contribute to the emerging body of knowledge on the role of RECs in improving the affordability, sustainability and security of the Dutch electricity grid.

1.3. Alignment with the COSEM Programme

This research aligns closely with the master's programme in Complex Systems Engineering and Management (CoSEM) at TU Delft by addressing energy communities (RECs), which are inherently complex sociotechnical systems. In such systems, participants interact with decentralized energy technologies while being influenced by social, economic, and regulatory factors. Tackling the challenges of grid congestion and the energy trilemma in this context requires a multidisciplinary and holistic approach, which the CoSEM programme equips students to handle.

The skills and tools gained from CoSEM courses like Complex Systems Engineering, Electricity and Gas Markets, and Energy Optimisation are directly applied in this research. These courses provide a strong foundation in understanding the interplay between technical infrastructure, market forces, and policy frameworks. By leveraging this knowledge, the research will effectively model Renewable Energy Communities (RECs) and propose design and operation strategies that enhance grid flexibility and optimise the use of decentralized energy resources. Ultimately, this research contributes to addressing the grid congestion issues that the Netherlands faces, in line with CoSEM's mission of integrating technology, systems thinking, and management for complex societal challenges.

1.4. Research Outline

This thesis is organized into seven chapters. The Introduction outlines the background, problem statement, and research objectives. The Literature Review explores existing research on Renewable Energy Communities, focusing on the Core Concepts and identifying gaps in energy system optimisation for RECs addressed in this study. Moreover, in this chapter the research questions are given. The Methodology describes the optimisation approach, modelling environment and our modelling approach, describing how we answer the sub questions. The Model Development chapter describes the conceptualization, formalization, implementation and usage of the optimization model using multi-objective linear programming (MO LP) in Calliope. The Results chapter presents findings from the model, including trade-offs visualized through Pareto fronts, clustering to identify representative scenarios, and analyses of design and operational dynamics. The discussion section describes how our results relate to the literature, what the research implications are and what limitations should be taken into considerations when interpreting the results. Thereafter, the Discussion synthesizes findings to answer the sub-questions and the research question. This chapter ends in recommending future work directions. Additional analyses and information are given in the Appendix.

2. Literature Review

This chapter provides an in-depth review of the core concepts, state-of-the-art research, and research gaps in the context of Renewable Energy Communities (RECs). By exploring the existing literature, we aim to establish a foundation for understanding the dynamics of RECs and their role in addressing the energy trilemma: affordability, sustainability, and security. The chapter also identifies knowledge gaps that this research seeks to address. It concludes by giving the research question and sub-questions.

2.1. Core Concepts

We describe five key concepts critical to understanding the dynamics of energy systems in the context of Renewable Energy Communities (RECs). These include Distributed Energy Resources (DERs), grid congestion, flexibility, RECs, and the Energy Trilemma.

2.1.1. Distributed Energy Resources

Traditionally, electricity grids were designed for a one-directional flow of energy, from centralized fossil-fuel power plants to consumers. However, the growing penetration of decentralized energy resources (DERs) has drastically altered these dynamics (Hennig et al., 2023; Tweede Kamer der Staten-Generaal, 2023). Distributed Energy Resources (DERs) refer to small-scale energy technologies that generate, store, or manage electricity and are typically connected to the lower-voltage distribution grid (Moncada et al., 2017; Ponnaganti et al., 2023). These technologies aim to enhance energy affordability, sustainability and grid security. Common examples include rooftop PVs, Batteries, EVs and smart appliances like heaters or thermostats (Energy Agency International (EIA), n.d.). DERs can be owned and operated by individual households, businesses, or communities.

2.1.2. Grid Congestion

Grid congestion occurs when the capacity of the grid to transport electricity is insufficient to meet demand or accommodate supply at a given time. This can manifest in two forms: 1) in-feed congestion, which occurs when the grid cannot absorb the electricity produced by renewable energy sources like solar or wind, and 2) consumption congestion, which happens when demand surpasses the grid’s ability to supply electricity (Estanqueiro et al., 2023; Hennig et al., 2022; Hennig et al., 2024).

In urban areas, where renewable energy production and electricity demand are often highest, grid congestion is increasingly frequent (Rijksoverheid, 2024). The primary congestion-related concern in the urban low-voltage (LV) grid is capacity shortages. Voltage issues, on the other hand, are more prevalent in rural settings where long cable lengths and high resistance increase the likelihood of under- or over-voltage problems (Rijksoverheid, 2024). This capacity shortage is mostly noticed in transformers that often become overloaded due to the increased demand from DERs. This overloading can result in accelerated degradation or damage to grid components, causing power outages or disruptions (Rijksoverheid, 2024).

2.1.3. Flexibility

One of the ways to make use of the existing grid infrastructure more efficiently is by using flexibility measures. There is no single definition of energy flexibility (Plaum et al., 2022). However, in the context of energy systems, flexibility refers to the grid's ability to adapt to fluctuations in supply and demand (Backe et al., 2022). In this thesis, we identify three types of flexibility:

1. Demand-side management (DSM) strategies, where consumers are incentivized to shift their energy use to off-peak times, reducing strain on the grid during high-demand periods (Alabi et al., 2023; Plaum et al., 2022; Ponnaganti et al., 2023).

2. Battery Energy Storage Systems (BESS), where excess energy generated during periods of low demand is stored and released during peak times. Storage systems can help balance supply and demand, reducing the need for costly grid upgrades. In other words, large-scale battery systems, as well as distributed storage solutions such as EV batteries, can provide valuable flexibility to the grid (Alabi et al., 2023; Plaum et al., 2022; Ponnaganti et al., 2023).

3. Interconnection allows us to balance supply and demand more effectively by selling excess energy or buying energy during shortages (Backe et al., 2022).

2.1.4. Renewable Energy Communities

Renewable Energy Communities (RECs) are legally defined entities that enable local generation, consumption, and storage of renewable energy within a community. Under EU directives like the Clean Energy Package (Directive (EU) 2019/944), RECs are formally recognized as organizations that allow citizens, businesses, and local entities to collaboratively generate, store, and share energy. Setting up a Renewable Energy Community (REC) in the Netherlands is possible, with around 700 energiecoöperaties (energy cooperatives) already in place.

To obtain a comprehensive view of the technical definition of a REC, we evaluate a range of technological components that could be integrated into a REC. The table in Appendix A shows the components considered, their inclusion status, and the rationale for each decision. As per the components we consider, throughout this thesis, energy refers specifically to electricity. While thermal energy systems (e.g., district heating, heat pumps, and thermal storage) can play a crucial role in local energy flexibility, this study focuses exclusively on electricity-based congestion, pricing, and optimization mechanisms. The role of thermal energy in RECs is acknowledged as a relevant but out-of-scope aspect that could be addressed in future research.

Renewable Energy Communities (RECs) differ from individual electricity consumers in their market structure and trading mechanisms. Unlike individual consumers who purchase electricity through retail contracts, RECs enable direct energy sharing among participants without intermediaries (Energy Agency International (EAI), n.d.). This optimises local energy flows, maximizes self-consumption, and reduces reliance on external grid imports.

Furthermore, a key advantage of RECs is their ability to aggregate demand and generation, allowing them to operate as a single market entity when trading with the MV grid. This aggregation improves efficiency and enables participation in markets, where RECs can sell excess electricity or engage in demand-side response programs (Hennig et al., 2023; Lampropoulos et al., 2019).

However, national regulations vary regarding the tariff structures for internal REC transactions. While some frameworks allow flexible pricing within the community, others impose grid tariffs even on locally exchanged energy, reducing financial incentives for self-consumption and internal optimization (Crowley et al., 2023; Tweede Kamer der Staten Generaal, 2024). In the Netherlands, RECs face similar limitations. Internal energy sharing is permitted, but interaction with the mid-voltage (MV) grid must be done through recognised market entities such as aggregators, retailers, or balancing responsible parties, as direct market access is often restricted by regulations (DIRECTIVE (EU) 2019/ 944, 2019; Garavaso et al., 2021).

This thesis considers RECs as electricity-based communities operating within the low-voltage (LV) grid, where internal energy sharing occurs freely without direct financial settlements due to the increased complexity but limited relevance to the research topic. We identify RECs act as a single aggregated entity when interacting with the MV grid. We assume that the centralised entity can import, and export based on day-ahead market prices, limiting the scope to only this national market instead of intra-day and flexibility markets that can be added in future research. This framework evaluates the potential to of RECs to enhance affordability, sustainability, and grid security under current simplified regulatory and market barriers that affect their real-world implementation.

2.1.5. The Energy Trilemma

The Energy Trilemma, as conceptualized by the World Energy Council (WEC), evaluates the ability of countries to deliver secure, affordable, and environmentally sustainable energy systems. This is formalized in the annually published Energy Trilemma Index (ETI), which ranks nations based on three core dimensions (Song et al., 2017).

- Energy Affordability and Equity: Measures the accessibility and affordability of energy for the entire population, focusing on providing equitable energy access.
- Environmental Sustainability: Examines energy efficiency on both the supply and demand sides and assesses progress in adopting renewable and low-carbon energy sources.
- Energy Security: Reflects the reliability of energy infrastructure, the management of domestic and external energy supply, and the ability to meet both present and future energy demands.

In this thesis, these dimensions are simplified for applicability to the Renewable Energy Community (REC) context:

- Affordability: focuses on minimizing the monetary cost of the system, including costs associated with investments in technologies like solar PV and storage operational decisions such as grid imports. While equity is a crucial consideration in broader contexts, this study emphasizes cost optimization rather than accessibility.
- Sustainability: is represented by the reduction of CO_2 emissions because of REC operations. Broader up- and downstream sustainability metrics are excluded from the analysis.
- Security: is simplified to focus on the management of local transformer usage to prevent grid congestion as we observe that congestion in urban areas is mainly caused by capacity shortages of transformers.

This conceptualisation is given below in Figure 2.

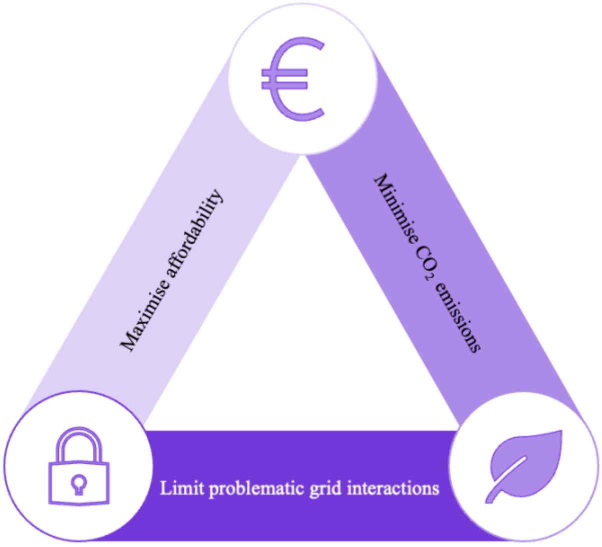

Figure 2: Visualisation of the Energy Trilemma in the context of this thesis.

2.2. State-of-the-art

The state-of-the-art section of the literature review in this thesis aims to identify research gaps related to the balancing of the energy trilemma in the context of the design and operation of urban Renewable Energy Communities (RECs). However, the fragmented, interdisciplinary nature of this emerging research field posed significant challenges in conducting a systematic literature review. Terms and concepts relevant to RECs often span multiple disciplines, including optimization, electrical engineering, and social sciences, with inconsistent or field-specific terminology complicating structured searches.

Traditional systematic approaches, such as database queries using predefined keywords and Boolean operators (e.g., "energy community" OR "microgrid" AND "optimisation" OR "Multi-Objective", AND "Energy Trilemma") resulted in either an overwhelming number of unrelated results or an insufficient pool of relevant studies. Additionally, manual scanning revealed that many articles used unique words further fragmenting the search process.

To address this, an unsystematic but targeted approach was adopted, which allowed for a more practical exploration of the literature within the constraints of the study. This method involved:

1. Starting with prominent papers: Initial papers recommended by supervisors and key foundational studies provided a starting point for understanding the field.

2. Snowballing: References cited in these initial papers were systematically explored to identify additional relevant studies.

3. Targeted search: Google Scholar was used as the primary search engine, given its broader indexing and alternative algorithmic approach compared to Scopus or Web of Science.

4. Expert judgement: Manual selection and evaluation of papers were performed based on their relevance to the specific scope of this thesis, prioritizing works that directly addressed REC design, optimization, or energy system modelling.

While this approach does not conform to the standards of a systematic review, this review aimed to contextualize and address specific research gaps, not to provide an exhaustive review of the field. By clearly delineating the scope and methodology of this literature review, this thesis acknowledges the inherent limitations of an unsystematic approach while ensuring its relevance within the constraints of the study.

Concluding, this section identifies the strengths and weaknesses in existing modelling approaches for balancing the energy trilemma in urban Renewable Energy Communities (RECs).

2.2.1. Affordability

Affordability is a key driver for the adoption of RECs, as they aim to reduce energy costs for participants by leveraging local energy generation, storage, and consumption.

Strengths in Affordability-Focused Research

One of the primary strategies for cost reduction in RECs is local energy generation, particularly through shared solar photovoltaic (PV) systems. Awad & Gül (2018) and Garavaso et al. (2021) show that shared solar installations can significantly lower energy bills for households by enabling them to generate their electricity, reducing reliance on the main grid. These studies emphasize that optimizing the size and operation of shared solar systems, especially when paired with battery storage, can maximize cost savings. Similar findings were reported by Bâra & Oprea (2024) who discussed value-sharing mechanisms in heterogeneous energy community archetypes to enhance cost efficiency.

Demand-side management (DSM) is another approach to enhancing affordability. (Chakraborty et al. (2020) demonstrated that a coordination mechanism within a REC could reduce price spikes in distribution grids, leading to cost savings. Lampropoulos et al. (2018) discussed how aggregators could offer flexibility services, enabling communities to adjust consumption in response to market signals, further reducing costs.

Battery Energy Storage Systems (BESS) also play a critical role in enhancing affordability by allowing communities to store excess renewable energy and use it during peak pricing periods. (Weckesser et al. (2021) found that optimal sizing of batteries within RECs can lead to significant cost reductions, enabling participants to store surplus energy for later use and avoid higher grid prices. This finding is confirmed by Secchi et al. (2021), who explored multi-objective optimization to balance cost savings with operational constraints for BESS.

Gaps in Affordability-Focused Research

Despite these clear benefits, existing studies often fall short when considering broader real-world scenarios. Awad & Gül (2018) and Garavaso et al. (2021) primarily focused on cost optimization without sufficiently integrating environmental impacts or grid stability. This narrow focus may inadvertently lead to increased reliance on cheaper, non-renewable energy sources during periods when local generation is insufficient, counteracting sustainability goals.

Similarly, Chakraborty et al. (2020) and Lampropoulos et al. (2018) emphasized cost savings through DSM but did not fully address the variability and reliability of renewable energy sources. Cost reductions achieved through demand flexibility do not inherently improve grid stability, particularly when integrating large-scale renewable resources that introduce supply fluctuations. Without addressing these fluctuations, cost-optimised RECs may still face reliability issues, undermining affordability. This shortcoming was noted by Canizes et al. (2023) who pointed out that the economic viability of local RECs depends on their ability to balance cost with grid resilience.

2.2.2. Sustainability

Sustainability is a core pillar of RECs, aiming to reduce carbon emissions and promote the integration of renewable energy sources (RES).

Strengths in Sustainability-Focused Research

Maximizing local renewable energy use is a primary strategy for improving sustainability in RECs. Backe et al. (2022) and Crowley et al. (2023) argue that local energy generation reduces dependence on centralized, fossil-fuel-based power plants, cutting carbon emissions by e.g. integrating solar PV.

Energy storage is another critical factor in sustainability. Weckesser et al. (2021) found that efficient battery usage can significantly increase the share of renewables in the local energy mix, reducing carbon intensity. Similarly, Azimi & Salami (2021) proposed frameworks for energy hubs that optimise renewable energy use but acknowledged that real-world integration requires consideration of technical constraints.

Demand-side management (DSM) can also support sustainability by aligning consumption with renewable energy availability, minimizing fossil fuel reliance. Ponnaganti et al. (2023) and Plaum et al. (2022) explored how DSM can improve sustainability by shifting usage to off-peak periods or times of high renewable generation. These strategies help increase the utilization of renewable energy sources, thus decreasing the need for fossil-based backup power.

Gaps in Sustainability-Focused Research

Despite progress, there are still limitations in how current sustainability research addresses other dimensions of the energy trilemma. Many studies prioritize increasing the share of renewable energy without fully considering cost and grid stability. For instance, Backe et al. 2022 demonstrated decarbonization potential but did not address the financial implications, which could lead to increased energy costs. This trade-off was also noted by Finke et al. (2024), who argued that models focusing exclusively on sustainability often overlook practical economic considerations.

Additionally, higher sustainability might lead to increased operational costs or require extensive infrastructure upgrades, raising affordability concerns. Ponnaganti et al. (2023) and Azimi & Salami (2021) discussed optimizing renewable energy integration but did not sufficiently explore how to maintain grid stability amidst high shares of variable renewables. Their solutions often assume ideal conditions without factoring in grid or peak demand. Crowley et al. (2023) examined how RECs could maximize renewable energy use and provide grid services, yet did not consider cost implications or how to manage low renewable output periods, highlighting a need for more comprehensive models that integrate sustainability, cost, and security.

2.2.3. Energy Security

Ensuring energy security is crucial for RECs, as they depend on variable renewable energy sources that create fluctuations in supply.

Strengths in Energy Security-Focused Research

Integrating energy storage systems is one of the primary strategies for enhancing energy security. Research by Weckesser et al. (2021) and Rodrigues et al. (2020) highlights that strategically sizing and placing storage units within RECs can significantly enhance grid reliability, providing backup power during outages or when renewable generation dips. Azimi & Salami (2021) discussed flexibility indices that help manage variability, ensuring consistent power output.

Demand-side management (DSM) also contributes to energy security by shifting consumption to off-peak periods, reducing grid stress. Crowley et al. (2023) and Plaum et al. (2022) explored how DSM can stabilize the grid, especially in scenarios with high penetration of intermittent renewable energy. Local energy consumption, as discussed by Fouladvand et al. (2022), can decrease reliance on the national grid, providing more resilience in underserved or congested areas.

Real-world examples, demonstrate how energy storage and DSM can improve resilience by maintaining local power supplies even during broader grid outages (Bonfert, 2024). These cases illustrate the practical benefits of integrating flexibility solutions to enhance energy security in RECs.

Gaps in Energy Security-Focused Research

Despite advances, there are significant gaps in research on energy security within RECs. Many studies emphasize technical solutions but do not fully address economic or operational challenges. High costs of installing and maintaining energy storage systems, for instance, can make them less accessible to smaller communities. As noted by Bonfert (2024), economic feasibility must be considered to make these solutions practical.

Additionally, models for enhancing energy security often overlook interactions between different energy resources within a community. Stegen et al. (2024) examined the benefits of distributed energy resources (DERs) for grid stability but did not explore how these systems balance with conventional grid infrastructure. Similarly, Estanqueiro et al. (2023) proposed technical solutions for integrating renewables but did not fully address economic aspects, underscoring the need for more holistic approaches that combine technical feasibility with financial viability.

2.3. Research Question

Although significant progress has been made in addressing affordability, sustainability, and energy security within RECs, existing research often focuses too narrowly on one dimension of the energy trilemma without adequately integrating the others. This limited approach can lead to solutions that are not viable in terms of the other dimensions. This research should, therefore, prioritize comprehensive models that enable exploring the trade-offs across all three pillars, ensuring that RECs can provide affordable, sustainable, and reliable energy solutions. In this context, the following research question is formulated:

How can Dutch urban Renewable Energy Communities be designed and operated to enhance energy affordability, sustainability and security?

2.4. Research Approach

This research is built around a broadly applicable modelling approach. This was chosen as a common limitation in the literature on optimising the design and operation RECs, is the narrow focus on specific case studies, which restricts the generalisability of the findings. Several studies, such as Secchi et al. (2021) have developed bi-objective optimization models for RECs that maximize self-sufficiency and minimise BESS capacity, but these models remain constrained by localized data and configurations. Similarly, studies like Reijnders et al. (2020) and Stegen et al. (2024) provide valuable insights into localized energy community configurations, but the scope of their research is often too narrow for generalization across diverse urban environments. As a result, policymakers and practitioners are limited in their ability to apply these findings to various contexts, particularly in the Dutch setting.

The need for broader, generalizable data is further emphasized by research from Anfinson et al. (2023) and Backe et al. (2022), who stress the importance of scaling empirical studies to develop more adaptable and flexible REC models. Therefore, research should focus on developing models and frameworks that incorporate generalized data, allowing for adaptable solutions that can be applied to multiple (urban) contexts.

Thus, given the lack of generalisable data in the literature, the methodology is built around a context-adaptable, broadly applicable modelling approach. This approach uses archetypal RECs, incorporating generalised data rather than relying solely on specific case studies, to allow for a more comprehensive exploration of REC potential across various urban environments. Here we will add the novelty of finding a way to optimise the system design and operation for the variables of the energy trilemma, which has been identified as lacking in the literature review.

2.5. Sub Questions

The modelling approach aims to answer the research question. This is done by answering three sub-questions which structure the thesis. The sub-questions are a result of the research gaps identified in section 2.2. The sub-questions are elaborated on in the methods section and stated below.

1. *What are the components and mechanisms that are to be considered when designing a generalisable Renewable Energy Community in the Dutch urban context?*

2. *How can we mathematically optimise the design and operation of a Renewable Energy Community for dimensions of the Energy Trilemma (affordability, sustainability, and grid security)?*

3. *What are the trade-offs between the most promising design and operation options for the generalised Renewable Energy Community?*

3. Methods

This research employs a structured modelling approach to explore the design and operation of Renewable Energy Communities (RECs) within urban contexts. Given the complexity of integrating RECs into existing energy grids, modelling serves as a vital tool for simulating interactions and analysing various strategies.

Due to this complexity, this research employs a normative modelling approach, focusing on identifying optimal strategies within defined objectives and constraints, rather than replicating observed real-world behaviour. Unlike descriptive models, which aim to mirror historical or current system dynamics, normative models are designed to guide how systems should behave under specific scenarios. The emphasis lies not on predicting exact outcomes but on understanding system behaviour under varying assumptions and constraints. This approach is particularly relevant in the context of energy systems, where uncertainties are significant, and decisions have long-term consequences (Finke et al., 2024; Lombardi et al., 2020).

As aforementioned, we want to design and operate RECs in line with the three pillars of the energy trilemma: affordability, sustainability, and energy security. This section describes the optimisation approach, the modelling environment, and the modelling approach. In Chapter 4 we describe how we develop the model step by step via the four phases described in this section. The resulting model is deployed in Chapter 5 *Results.*

3.1. Optimisation Approach

Modelling the design and operation of Renewable Energy Communities (RECs) can be approached through various methods, each with its strengths and limitations. Techniques such as Agent-Based Modelling (ABM), Mixed-Integer Linear Programming (MILP), and Multi-Objective Linear Programming (MO LP) are commonly used in energy system research.

In this research, we adopt a Multi-Objective Linear Programming (MO LP) approach. MO LP provides a balance between computational efficiency and the ability to explore trade-offs between competing objectives, such as cost, sustainability, and energy security, the core dimensions of the energy trilemma. By using MO LP, we can represent the optimization problem mathematically while maintaining clarity and tractability in model interpretation.

However, MO also has limitations. Assigning objective weights beforehand can introduce bias, especially if stakeholder preferences are unknown or conflicting, and adjusting these weights to reflect multiple perspectives can limit the analysis’s flexibility. Additionally, as the number of objectives increases, interpreting the trade-off curves becomes more complex, potentially complicating decision-making (Finke et al., 2024; Lombardi et al., 2020). While MO offers clear insights into the boundaries of feasible trade-offs, it relies on initial assumptions that may not fully accommodate fluid or uncertain priorities.

Still, the choice for MO LP aligns with the goal of this thesis: to identify optimal strategies for REC design and operation while balancing multiple objectives. The simplicity and transparency of LP formulations allow for robust sensitivity analyses and scenario testing, ensuring that results remain adaptable and insightful across varying conditions.

3.2. Modelling Environment

The model is developed using Calliope, a Python-based energy systems modelling tool developed at TU Delft, which enables detailed linear optimization of energy systems (Pfenninger & Pickering, 2018). The work by Pfenninger & Pickering (2018), explored cost-efficient energy system modelling using Calliope. This lacks the integration of environmental sustainability and grid security considerations. However, Calliope offers a highly flexible and customizable platform for energy system modelling, designed to handle complex, multi-scale systems. Therefore, the modelling environment can be adapted to include these variables in the objective function.

One of Calliope's key technical advantages is its ability to represent energy system components as nodes in a network, each with defined constraints, costs, and efficiencies. The model then optimises the design and operation of these components over time based on user-defined objectives.

What makes Calliope particularly valuable for this thesis is that it eliminates the need to manually define complex mathematical relationships between components. This simplifies the modelling process while still capturing important technical aspects like energy flows, capacity limits, and constraints of Distributed Energy Resources (DERs). Moreover, Calliope supports the optimisation of both investment (design) decisions (i.e. determining the optimal size and location of energy generation or storage technologies) and operational decisions (i.e. dispatching energy resources).

In the context of this research, this approach allows us to focus on higher-level questions about energy community design and operation. Rather than manually modelling the mathematical interactions, we can leverage Calliope’s framework to formulate different objective functions, such as minimizing monetary cost, CO_2, or congestion in an efficient manner. This makes scenario analysis possible within the given timeframe of the thesis, enabling us to test various priorities given to Energy Trilemma pillars and explore the impact on the system design and operation.

3.3. Modelling Approach

This research integrates qualitative and quantitative methods. Qualitative data from the literature will provide context and validation for the quantitative optimisation performed using the LP optimization approach. To build a model which addresses the research question and sub-questions, we split the modelling into separate phases. We take inspiration from the book by Dam, Nikolic, and Lukszo (2012) on Agent-Based, and adapt it to fit the LP optimisation modelling process. The book contains four phases to ensure we build a comprehensive and accurate model of the sociotechnical system. In this section, we explain our adaptation. In Chapter 4, we describe how we execute these phases to develop the optimisation model.

3.3.1. Phase 1: Conceptualisation

The Conceptualisation phase builds on the literature review done in section *2.1.4. Renewable Energy Communities* where identify essential elements of RECs. Phase 1 goes beyond merely identifying components. It aims to formalise these findings into an archetype of an urban REC that is both generalisable and comprehensive. The process of conceptualising the REC, thus, involves gathering typical, generalisable data for all relevant components and user types.

The conceptual model developed in this phase will serve as a blueprint for the formalisation and implementation processes in the following phases. This ensures that the research approach remains grounded in both theoretical insights and practical data, enabling the design of a REC that can meet the goals of affordability, sustainability, and energy security.

This phase thus answers sub-question 1:

"What are the components and mechanisms that are to be considered when designing a generalisable Renewable Energy Community in the Dutch urban context"

We answer the question by combining the components and mechanisms into a simple visualisation that represents a generalisable REC in the Dutch urban context.

3.3.2. Phase 2: Formalisation

The Formalization phase transforms the conceptual model developed in Phase 1 into a formal, mathematical, or computational representation. As described by van Dam et al. (2012), formalization involves translating the system's conceptual understanding into a framework suitable for simulation or optimization. In this phase, we focus on defining the mathematical equations required to model and optimise Renewable Energy Communities (RECs).

Building on the archetype established in Phase 1, we translate the REC into a formal model that can be solved using linear programming techniques within the Calliope modelling environment. This process involves defining objective functions, decision variables, and degrees of freedom to address the energy trilemma: affordability, sustainability, and grid security. Throughout this phase, we iteratively verify the model in collaboration with experts in linear optimization to ensure it accurately reflects both theoretical insights and practical constraints. By the end of this phase, the mathematical foundation of the REC model is established, and ready for analysis in subsequent phases.

This phase thus answers sub-question 2:

"How can we mathematically optimise the design and operation of a Renewable Energy Community for dimensions of the Energy Trilemma (affordability, sustainability, and grid security)?"

3.3.3. Phase 3: Implementation

The Implementation phase applies the formalized model to explore the trade-offs between design and operation options for Renewable Energy Communities (RECs). To do so, we use multi-objective optimization (MO) to generate Pareto fronts, which illustrate the trade-offs between affordability, sustainability, and grid security. By varying the weights assigned to each objective, we create a range of Pareto-optimal solutions. These solutions are clustered to identify representative scenarios, ensuring a diverse selection of configurations for further analysis.

Once representative scenarios are selected, we analyse them to uncover patterns and trade-offs in REC design and operation. This includes evaluating similarities in system configurations and operational strategies across scenarios to understand how different priorities within the energy trilemma impact system behaviour.

3.3.4. Phase 4: Usage

The fourth phase evaluates the robustness, validity, and applicability of the model's outcomes through sensitivity analysis. The goal is to test the system's behaviour under varying conditions, ensuring that the results remain reliable and generalizable across different scenarios. This phase specifically addresses the uncertainties inherent in energy systems, such as variability in demand, pricing, and infrastructure capacity, and assesses how these factors influence Renewable Energy Community (REC) design and operation.

The sensitivity analysis ensures that the recommendations derived in earlier phases remain valid across a range of realistic and extreme scenarios. By exploring how parameter variations influence system design and operation, this phase offers actionable guidance for policymakers and stakeholders, emphasizing strategies that balance the energy trilemma in uncertain environments.

By collating the results from phases 3 and 4 we can answer sub-question 3:

"What are the trade-offs between the most promising design and operation options for the generalised Renewable Energy Community?"

Having established this methodology, the subsequent sections will execute and describe each phase in detail, providing insights into the modelling of the design and operation optimization of RECs within the context of the energy trilemma. The simplified research flow diagram, giving an overview of these steps, is given below in Figure 3. The detailed version is found in Appendix B.

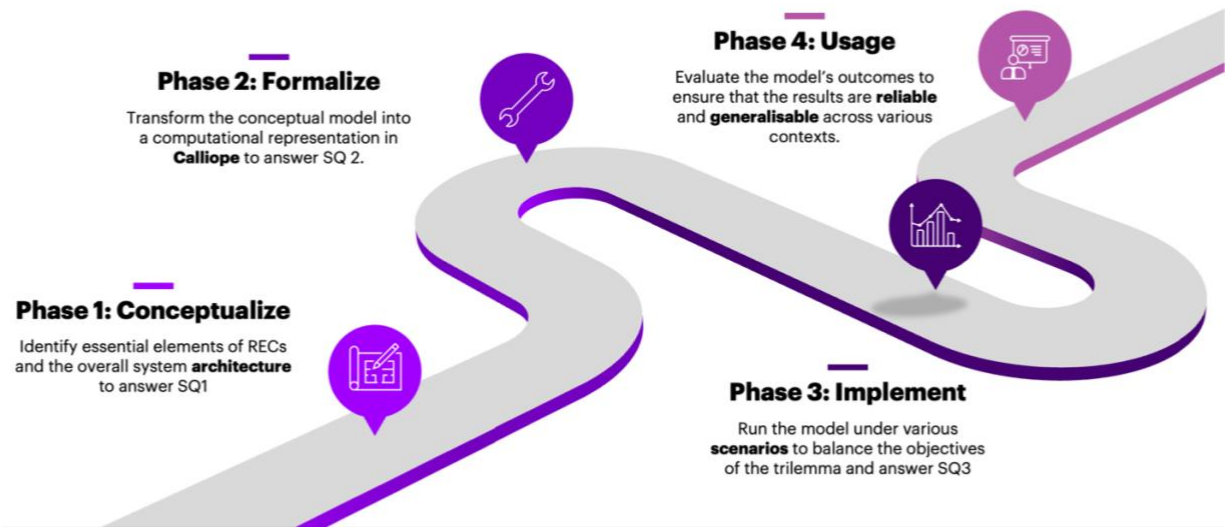

Figure 3: Research Flow Diagram based on van Dam et al. (2012).

4. Model Development

This chapter details the development of the Renewable Energy Community (REC) optimisation model. The model development follows the four-phase process: conceptualization, formalisation, implementation and usage, as previously outlined in section 3.3. First, the conceptualisation phase establishes a generalizable REC structure, identifying key components and their interactions. The formalization phase translates this structure into a mathematical optimization model, defining objective functions, decision variables, and constraints. Implementation then applies the model using a Multi-Objective Linear Programming (MO LP) approach, generating Pareto-optimal solutions that explore trade-offs across the energy trilemma. Finally, in the usage phase we deploy sensitivity analysis to assess the robustness of the results, ensuring that findings remain valid under varying assumptions and uncertainties. The results obtained from the model are given in Chapter 5.

4.1. Phase 1: Conceptualisation

The Conceptualisation phase aims to formalise an archetype of an urban REC that is both generalisable and comprehensive. We follow the structure of Calliope and discuss this phase following the description of the .YAML files as given by the model (Pfenninger & Pickering, 2018).

Following Calliope's categorization, we first describe the five technology types: (1) supply, (2) demand, (3) conversion, (4) storage, and (5) transmission. Thereafter we shortly describe which locations inherit which technology. These findings are translated into a conceptual model, depicted as a figure. The resulting conceptual model serves as a blueprint for the formalisation and optimisation processes in the following phases. The data and assumption sources are given in Appendix C to aid the description of the conceptualisation.

It is important to note that there are three types of power carriers in this system. We distinguish between power from the MV, power from the LV grid and power that is generated by PV panels. Although these all represent electricity, we do not want them to get intertwined due to their different properties (i.e. voltage). Also, we base all data on the year 2023, as it is the most recent data available to us.

4.1.1. Supply

Supply technologies encompass all energy sources feeding into the Renewable Energy Community (REC), including the mid-voltage (MV) grid, local solar PV generation, and unmet demand mechanisms.

Grid Power Import

The MV grid import is the primary external electricity source. It is assumed to have unlimited capacity, with hourly prices reflecting day-ahead market fluctuations provided by ENTSOE (2024). We base this simplification on similar research by Aghamohamadi et al. (2019); Chakraborty et al. (2020); and Qu et al. (2023). The energy price throughout the year is given in Figure 4.

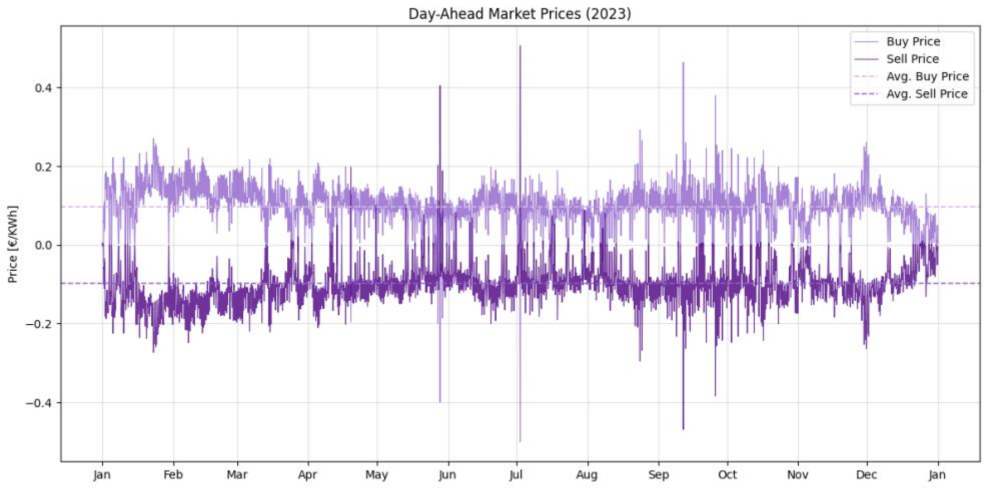

Figure 4: Hourly day-ahead prices for 2023.

Grid energy is assigned a CO_2 emission factor of 0.27 kg/kWh, based on STATISTA (2024), to penalise high reliance and promote sustainable alternatives. The emission factor is assumed to be static as we were not able to retrieve a time series for the Dutch national energy grid in 2023.

Solar Power

Local energy generation is achieved through Solar Power, which represents solar panels. Each household is assumed to have a maximum PV capacity of 6 kW, as per Rijksoverheid (2024), to simulate worst-case congestion scenarios. Time-based capacity factors derived from Renewables Ninja by Pfenninger & Staffell (2016) are used, incorporating a 10% parasitic loss to account for inverter inefficiencies. The hourly capacity factors are given in Figure 5.

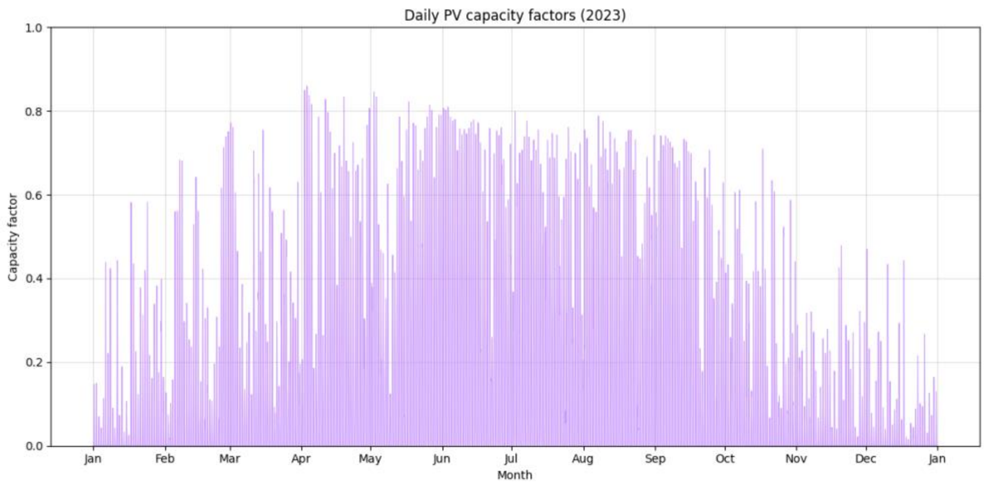

Figure 5: Hourly Solar Power Capacity factor for 2023.

Unmet Demand

Unmet demand acts as a penalty mechanism for scenarios where the system cannot meet energy needs. It is assigned a prohibitively high cost (1,000,000 € per kWh) to ensure the model prioritises configurations avoiding energy shortages. This approach allows us to track scenarios where technological capacity is insufficient to meet demand.

4.1.2. Demand

There are different types of demand to be considered in the model. We have identified (1) consumer demand, (2) grid exports and (3) curtailment from the literature.

Power Demand

Consumer energy demand fluctuates daily. We modelled this demand by using E1 (3x25A) and E2 (3x75A) archetypes defined by MFFBAS (2024) and aligned with Rijksoverheid's (2024) definitions for small-scale LV consumers. The E1 profile represents households (e.g., apartments, detached homes), and the E2 profile represents small businesses, institutions (like schools and clinics), and light industry. The dimensionless profiles were retrieved from the MFFBAS (2024) site and are given in Figure 6 & 7. These profiles are scaled up to annual demands of 2,500 kWh (E1) and 5,000 kWh (E2), capturing the variability of urban energy use per user.

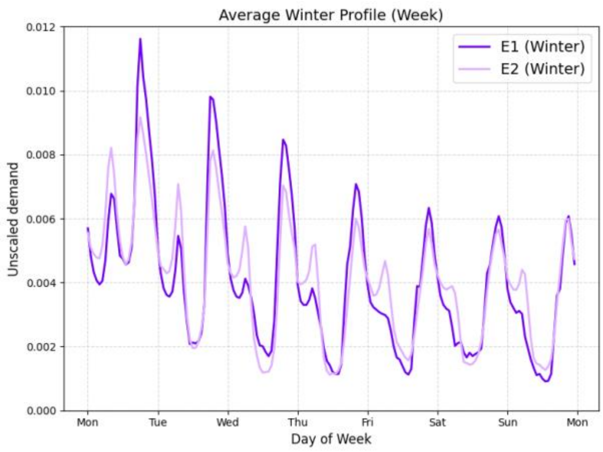

Figure 6: Demand factor in a winter week (MFFBAS, 2024).

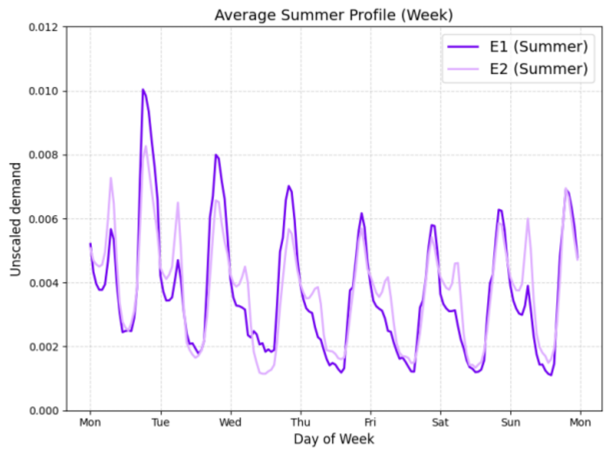

Figure 7: Demand factor in a summer week (MFFBAS, 2024).

Grid Power Export

Grid exports are modelled as an energy sink, allowing surplus electricity from the REC to be sold to the MV grid. The export price is inversely proportional to the day-ahead purchase price (ENTSOE, 2024). This means that exports are incentivized during high-price periods when grid demand is high. While this assumption simplifies market interactions, it does not fully reflect real-world conditions, as current regulations may require RECs to sell through intermediaries or aggregators rather than directly at day-ahead prices as previously described in Chapter 2.1.4. However, incorporating such regulatory constraints would add complexity without significantly altering the model's high-level insights.

Curtailment

Curtailment represents instances where local generation exceeds storage and export capacity. It is modelled as a zero-cost demand to track the unused potential of Solar Power generation. To prevent curtailment from creating an infinite sink, we introduce the Power_PV level, linking PV output to curtailment via a zero-loss transformer. Therefore, it is important to note that Solar Power indicates the solar panel's maximum potential output at time *t*, whilst PV is the amount of electricity produced by solar panels that enters the system. This approach allows us to measure curtailment at each timestep.

4.1.3. Conversion

Congestion in urban grids is primarily caused by transformer capacity shortages. The model simplifies this by focusing on transformer capacity as the bottleneck, without simulating cable routes or voltage issues.

Transformer In and Out

Due to model limitations, we define two transformers, one for buying from and another for selling to the grid. In practice, these operations would not occur simultaneously, rendering this modelling simplification functionally irrelevant in the simulation context.

The transformer converts MV power to LV power and vice versa, with a capacity of 400 kVA, representing typical urban transformers serving 200 connections (Bhattacharyya et al., 2008; Phase To Phase, 2021; Weckesser et al., 2021). An efficiency rate of 95% is applied to reflect operational losses (Bhattacharyya et al., 2008). This setup effectively represents the energy-sharing dynamics within the LV grid, where local consumption is unrestricted, but transactions with the MV grid are limited by transformer capacity.

Transformer PV

A zero-loss household-level transformer is introduced in the model to create a clear and traceable separation between household-level solar generation and the LV network, ensuring that energy flows remain structured and measurable. This component serves as a technical function in tracking the amount potential of Solar Power, the amount of curtailment and the amount of energy entering the LV system as previously discussed in section *Curtailment*.

4.1.4. Storage

The model includes MV storage and LV storage to enhance grid flexibility. MV batteries facilitate grid flexibility by deferring costly infrastructure upgrades and alleviating congestion, especially when coordinated with Distribution System Operators (DSOs) (Weckesser et al., 2021). Although MV storage may not be legally feasible, we included it due to the interest of Accenture.

LV batteries enhance the self-consumption of locally generated renewable energy, such as solar PV, and reduce electricity costs for individual users. However, their limited capacity restricts their ability to address broader grid issues, such as MV congestion management or voltage regulation (Weckesser et al., 2021). Instead, their primary utility lies in meeting localized energy needs efficiently.

Both types have a 95% round-trip efficiency and reflect real-world degradation with a 1% hourly discharge depth. Costs are based on €750/kWh for LV systems and €500/kWh for MV systems. Lastly, we assume a discharge-to-capacity ratio of 0.25, meaning batteries can sustain peak discharge for four hours. We base these numbers on studies by Berg et al. (2023), Pasqui et al. (2024) and Weckesser et al. (2021).

Because energy on the LV level can be shared freely according to our definition of a REC, the LV storage can be interpreted as either centralized or decentralized. In this model, the LV storage should, thus, be considered as system-wide storage, with specific distribution and ownership structures to be considered for future research.

4.1.5. Transmission

The LV grid is modelled as a radial configuration, representing typical urban electricity distribution networks (Phase to Phase, 2021). In a radial grid configuration, power flows from a single transformer to multiple end-users in a tree-like, unidirectional pattern, with each branch connecting to a cluster of consumers (Figure 8). Under high loads, the transformer can get congested, as each consumer cluster depends on a single path to the transformer. Although we do put limits on the flow capacity of the transmission lines, they are not expected to get congested (Bhattacharyya et al., 2008; Phase to Phase, 2021; Rijksoverheid, 2024).

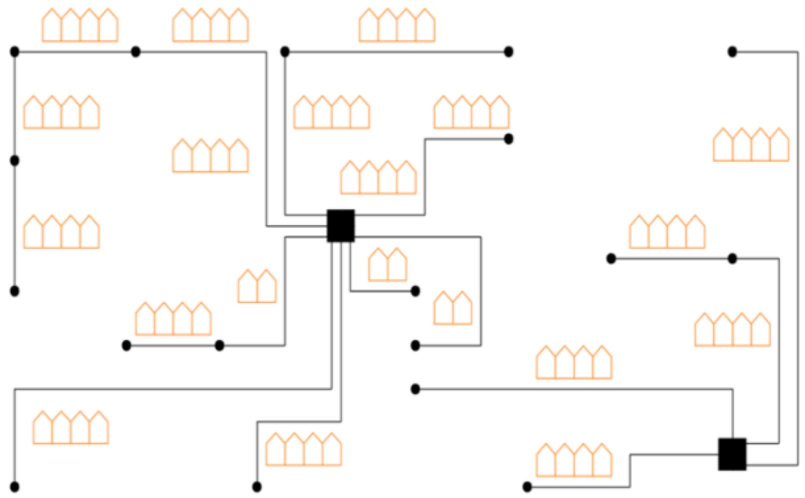

Figure 8: Radial LV configuration (Phase to Phase, 2021).

4.1.6. Locations

The model includes two types of locations: prosumer nodes, representing households or businesses with localized energy technologies, and a central transformer node, which connects the Renewable Energy Community (REC) to the mid-voltage (MV) grid. This configuration reflects the structure of an energy community, where electricity sharing is optimised within the community, and interactions with the wider grid are centralized at the transformer. The transformer in this model is assumed to support approximately 200 connections, based on similar papers (Bhattacharyya et al., 2008; Phase to Phase, 2021; Weckesser et al., 2021).

Within the REC, energy sharing is modelled as free flows within the LV system, allowing participants to exchange electricity without contractual restrictions. This design aligns with the market structure of RECs discussed in Section 2.1.4. where we describe that RECs operate differently from conventional electricity consumers. Rather than purchasing electricity through retail contracts, the community optimises local generation and demand, reducing reliance on the MV grid. When interactions with the external market occur, they are centralized at the transformer, where the REC acts as a single market entity, aggregating demand and generation (Directive (EU) 2019/944; Garavaso et al., 2021).

By structuring the REC in this way, the model captures the real-world market participation dynamics of RECs. However, it also simplifies real-world complexities, such as internal pricing mechanisms and regulatory constraints, which remain key challenges for practical REC implementation but are beyond the scope of this research (Crowley et al., 2023; Tweede Kamer der Staten-Generaal, 2024).

Prosumer Nodes

Prosumer nodes represent individual households or small businesses and include E1 and E2 archetypes, which account for 80% and 20% of the connections, respectively (Rijksoverheid, 2024). These nodes host demand, Solar Power, LV Battery Storage, and Curtailment technologies.

Transformer Node

The transformer node acts as the sole point of interaction between the REC and the MV grid, hosting grid imports and exports, MV battery storage, and unmet demand. By centralizing grid interactions at the transformer, the REC operates as a single market entity, optimizing energy flows within the community and only engaging with the wider grid for net imports or exports. This approach aligns with the market structure envisioned for energy communities under EU directives, where internal energy flows are managed collaboratively, and external transactions are handled as a collective as discussed in section 2.4.1.

The installed techs per node are summarised in Table 1.

Table 1: Installed techs per node.

Node	*Installed Techs*
Prosumers (e1, e2)	Power demand, PV transformer, Solar photovoltaic power, Battery Storage (decentral), Curtailment.
Transformer	Grid import, Grid export, Transformer In, Transformer Out, Battery Storage (central), Unmet Demand.

Network Design

To design a realistic and manageable LV system, the 200 connections are divided into five branches originating from the transformer, inspired by Figure 9, conceptualised by Phase to Phase (2021). This radial configuration mirrors typical urban electricity distribution networks, where power flows unidirectionally from a central transformer to end-users.

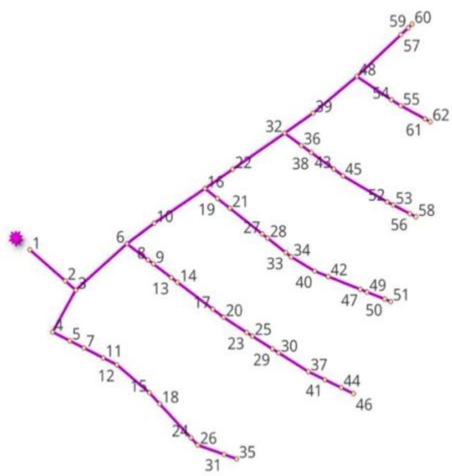

Figure 9: Typical radial configuration in Dutch urban context (Phase to Phase, 2021).

4.1.7. Generalisable Renewable Energy Community

In this chapter, we outlined the essential components and mechanisms involved in designing a generalizable Renewable Energy Community (REC) in the Dutch urban context. We discussed the integration of local solar generation, demand profiles, storage solutions, and the role of the transformer in managing congestion, all within a radial grid structure suited to urban low-voltage networks. To give an overview of the components and inputs we discussed, we have formulated Table 6 in Appendix C. A summarising visualisation of a generalisable Renewable Energy Community (REC) in the Dutch urban context is given in Figure 10.

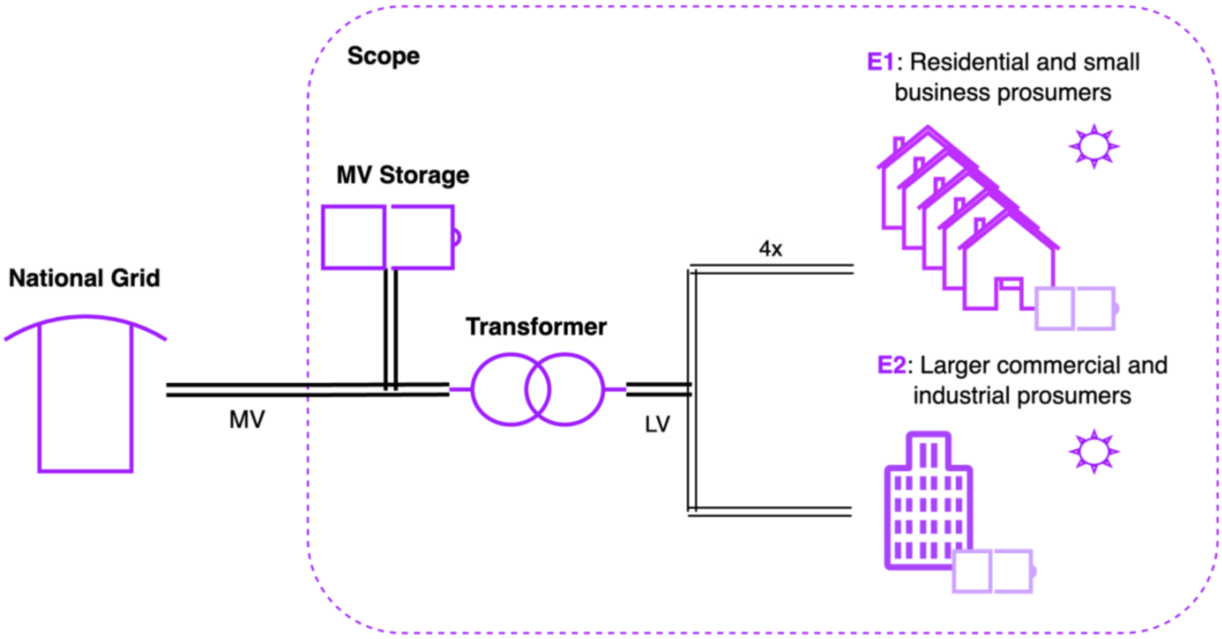

Figure 10: Generalisable Renewable Energy Community in the Dutch urban context.

4.2. Phase 2: Formalisation

In the Formalisation phase, we use the conceptual model of the Renewable Energy Community (REC) to formulate the mathematical multi-objective optimisation framework. This phase focuses on defining the optimization objectives and methods used to explore potential REC configurations, enabling us to address the energy trilemma of affordability, sustainability, and security. In this Formalisation phase, we focus on three critical components.

1. **Optimisation Approach**: We describe the objective function for the multi-objective optimisation.

2. **Decision Variables**: We mathematically specify the objective functions to capture the three primary goals of the energy trilemma: affordability, sustainability, and grid security.

3. **Degrees of Freedom**: We explicitly disclose which parameters can be adjusted to find optimal solutions in terms of design and operation in the context of the energy trilemma.

By formalizing the objective functions and selecting an appropriate optimization method, we enable the model to navigate the energy trilemma effectively, offering insights into the most viable design and operation options for Renewable Energy Communities in an urban context.

4.2.1. Optimisation Approach

In the context of Renewable Energy Communities (RECs), no universally optimal solution simultaneously maximizes affordability, sustainability, and grid security. These objectives inherently conflict, requiring careful balancing to achieve a solution that addresses all dimensions of the energy trilemma effectively.

Multi-objective optimization (MO) generates a set of solutions along a Pareto front. Each point on the Pareto front represents an optimal trade-off between objectives, such as affordability, sustainability, and grid security, illustrated in Figure 11 by (Finke et al., 2024). We create a Pareto front by assigning a weight to each objective, based on the priority given to the objective by for example decision makers in the system (Finke et al., 2024). MO allows us to therefore explicitly show the priority given to a dimension of the energy trilemma, and it's resulting Pareto optimal outcome.

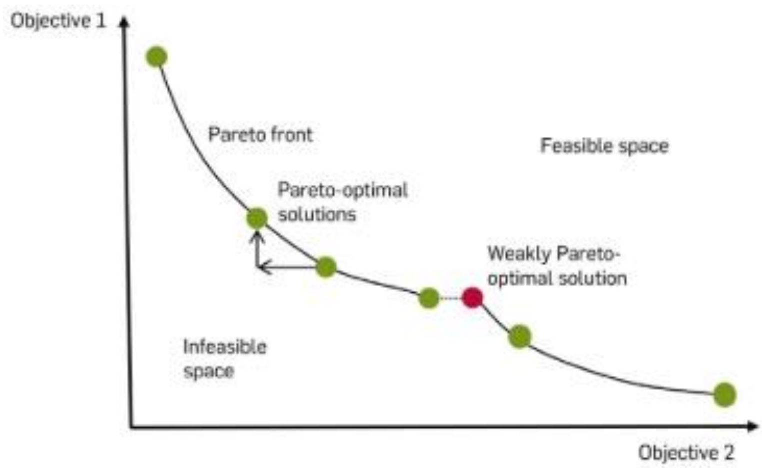

Figure 11 Pareto front for two objectives (Finke et al., 2024).

A Pareto-optimal solution ensures that improving one objective will worsen another, making this approach particularly effective for visualizing trade-offs. The slope of the Pareto front reveals how gains in one dimension impact the others, providing policymakers with a structured view of feasible compromises, which is especially valuable in complex energy systems where clear trade-offs are needed (Finke et al., 2024). The general mathematical notation of a MO LP optimisation is given in Equation 1 for context.

$$\text{Minimise } Z = \sum_i w_i * f_i(x) \tag{1}$$

$$x \in X \tag{2}$$

Where:

- Z : Total objective function value.
- $f_i(x)$: Represents each objective function.
- w_i : Is the weight assigned to each objective *i*.
- X : Is the feasible solution space defined by the constrains.

4.2.2. Decision Variables

In this section, we specify the objective function and decision variables that align with the energy trilemma dimensions: affordability, sustainability, and grid security. By formalising the objective function, we establish a mathematical foundation for assessing the trade-offs and synergies between the trilemma objectives. The overarching Equation (9) is split up over the sections and given at the end.

Affordability

Affordability in the model is represented through cost minimization variables, which include both operational and capital expenditures. Specifically, we define:

- Operational costs are determined by energy imports from the mid-voltage (MV) grid, which are governed by hourly day-ahead market prices.

- Capital costs for infrastructure installations, such as solar PV, storage, and transformers. These installation costs, fixed at the start of the model, represent long-term investments that influence the overall financial feasibility of the REC. We assume no costs associated with existing infrastructure.

Notably, the model does not include operational costs for solar PV or battery storage. While real-world systems have maintenance costs, these are excluded for simplification. Furthermore, the model assumes zero marginal costs for solar PV generation and no lifetime efficiency degradation of solar PV and battery storage. This means that once installed, these technologies operate without additional costs. The only financial considerations for these assets are their initial capital costs, which are fixed at the start of the model.

Together, these variables allow the model to determine an optimal cost configuration, balancing the purchase and installation costs to ensure economic feasibility for REC participants. The mathematical formulations are given in Equations 3 - 5.

$$C_{op} = \sum_{t} P_{grid}(t) * Flow_{grid_{import}}(t) - P_{grid}(t) * Flow_{grid_{export}}(t) \tag{3}$$

$$C_{cap} = \sum_{i} C_{installation_i} * Capacity_i \tag{4}$$

$$C_{monetary} = C_{op} + C_{cap} \tag{5}$$

Where:

- C_{op} : Total operational costs from grid imports and exports.
- $P_{grid}(t)$: Day-ahead market price at time t for grid electricity.
- $Flow_{grid}(t)$: Electricity imported from or exported to the MV grid at time *t*.
- C_{cap} : Capital costs for infrastructure investments.
- $C_{installation,i}$: Installation cost of technology *i*.
- $Capacity_i$: Installed capacity of technology *i*.
- $C_{monetary}$: Total cost, combining operational and capital expenditures.

Sustainability

Sustainability is quantified through CO_2 emissions associated with energy imports from the grid. A CO_2 emissions factor is assigned solely to grid electricity, as local renewable generation (solar PV) is considered carbon-free within the model. The factor is time-independent, as CO_2 time series data for the Dutch electricity grid in 2023 was unavailable.

By minimizing the amount of energy imported from the MV grid, the model promotes the use of renewable sources within the REC, thereby reducing the carbon footprint of the community. The sustainability objective is thus captured by a cost on emissions that incentivizes renewable usage and is given in Equation 6.

$$C_{CO_2} = E_{grid} * \sum_{t} Flow_{grid_{import}}(t) \tag{6}$$

Where:

- C_{CO_2}: Total carbon cost from grid imports.
- E_{grid} : Emission factor in kg CO_2 eq/kWh.
- $Flow_{grid}(t)$: Electricity imported from or exported to the MV grid at time t.

Security

The Transformer Congestion Factor (TCF) is a novel concept introduced in this study to address a critical gap in modelling the grid security dimension of Renewable Energy Communities (RECs). In urban areas, grid congestion often arises from transformer overloading as discussed in section 2.1. While real-world congestion time series data could theoretically guide the optimization process, such data is either unavailable or highly location-specific, making it impractical for generalizable modelling.

To overcome this limitation, the TCF uses day-ahead market prices as a proxy for transformer congestion. This approach is based on the principle that market prices reflect the balance between supply and demand on the electricity grid. High day-ahead prices indicate periods of high demand, where transformer usage may already be strained, while low prices suggest low demand and reduced transformer load. The TCF is designed as a dimensionless indicator that dynamically adjusts the cost of transformer usage based on these market signals.

By linking transformer flow to price-based congestion probabilities, the TCF discourages excessive transformer usage during periods of high demand (and high prices) and encourages feed-in during low-demand (low-price) periods. This dynamic mechanism helps prevent congestion, ensuring that the REC operates within safe transformer capacity limits without requiring direct congestion measurements.

The novelty of the TCF lies in its ability to simulate congestion management without relying on specific grid data, enabling the model to be applied to a variety of urban contexts. Furthermore, the TCF provides a flexible tool for influencing REC behaviour, allowing the exploration of scenarios where transformer usage is minimised or optimised to align with grid stability objectives.

We mathematically formulate the TCF in Equation 7 and multiply it by the flow through the transformer to obtain an annual dimensionless cost indicator that we call the Transformer Congestion Indicator (TCI) in Equation 8.

$$C_{TCI} = \sum_{t} TCF(t) * Flow_{transformer}(t) \tag{7}$$

$$TCF(t) = \begin{cases} \dfrac{P_{max} - P_{grid}(t)}{P_{max} - P_{min}} & for\ imports \\ 1 - \dfrac{P_{max} - P_{grid}(t)}{P_{max} - P_{min}} & for\ exports \end{cases} \tag{8}$$

Where:

- C_{TCI}: Transformer Congestion Indicator, representing grid congestion costs.
- *TCF (t)*: Cost factor to penalise transformer usage a time *t*.
- $Flow_{transformer}(t)$: Electricity flowing through the transformer at time *t*.
- P_{min}, P_{max}: Minimum and maximum day-ahead market prices.

The time series of the conceptualised TCF is given in Figure 12.

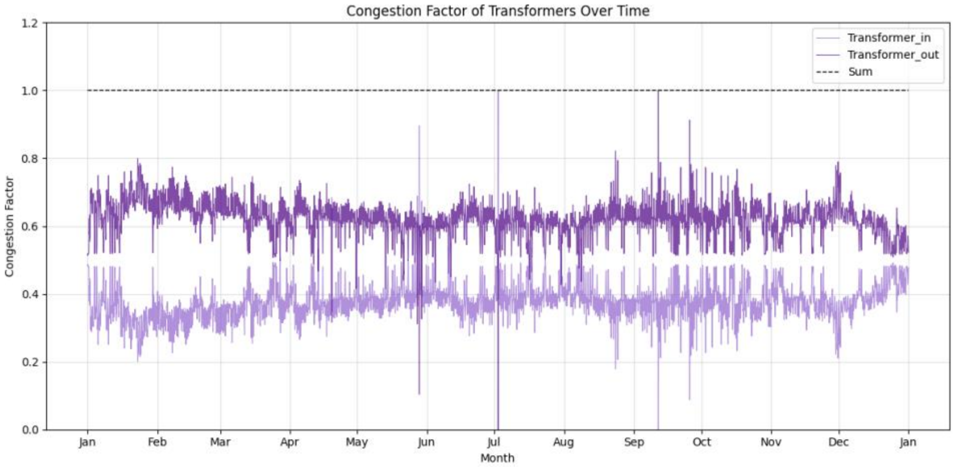

Figure 12: Hourly Transformer Congestion Factor (TCF) for 2023.

Objective Function

The objective function in this study balances the three dimensions of the energy trilemma: affordability, sustainability, and grid security. This is achieved by minimizing a weighted sum of the monetary costs, CO_2 emissions, and the transformer congestion indicator (TCI). By assigning weights to each objective, the model allows for prioritization of specific dimensions depending on stakeholder preferences or policy objectives. The resulting overarching mathematical formulation is given below in Equation 9.

Minimise: *Affordability* *Sustainability* *Security*

$$Minimise\ Z = \sum w_{monetary} * C_{monetary} + w_{CO_2} * C_{CO_2} + w_{TCF} * C_{TCF} \quad (9)$$

Where:

- Z: Overall objective function value.
- $w_{monetary}$: Weight assigned to affordability.
- w_{CO_2}: Weight assigned to sustainability.
- w_{TCF}: Weight assigned to grid security.

By systematically varying the weights in Equation 9, a Pareto front can be generated, representing the trade-offs between the objectives. Each point on the Pareto front corresponds to a unique configuration of weights, illustrating the compromises between affordability, sustainability, and grid security.

4.2.3. Degrees of freedom

The optimisation framework in this thesis leverages Calliope's capabilities to explore the design and operation of Renewable Energy Communities (RECs) in the context of the Energy Trilemma. The degrees of freedom in this model represent the critical decision variables that the optimisation process adjusts to identify optimal configurations and operational strategies. It is important to note, that Calliope optimises for design and operation simultaneously.

At the design level, the primary degrees of freedom involve the capacity sizing of solar photovoltaic (PV) systems and battery energy storage systems (BESS). This includes decisions on whether storage should be installed at the MV level (e.g., located at the transformer) or installed at the LV level (e.g., distributed across prosumer households).

On the operational side of the model, we have three categories of variables that optimise the REC. Battery Energy Storage Systems (BESS) can charge and discharge hourly. Energy transactions with the grid are determined hourly. Lastly, curtailment is applied when local renewable generation exceeds the capacity of storage and grid export, ensuring system balance and preventing overloading.

Together, these design and operational degrees of freedom enable the model to explore a wide solution space, identifying configurations and strategies that balance the competing priorities of the energy trilemma. By dynamically adjusting these variables, the model captures the trade-offs and synergies inherent in REC design and operation.

4.3. Phase 3: Implementation

The implementation phase applies the formalized optimization model to identify trade-offs between affordability, sustainability, and grid security in Renewable Energy Communities (RECs) using a multi-objective optimization (MO) approach. Each optimization run produces a solution based on specific objective weight combinations, forming a Pareto front that highlights trade-offs. Extreme points on the front represent single-objective prioritization, while central points reflect balanced trade-offs. Selected scenarios from the Pareto front provide insights into how varying priorities influence REC design and operation, offering a comprehensive understanding of trade-offs under different decision-making perspectives.

This chapter describes the following methods.

- How we assign weights to obtain the Pareto front.
- What scenarios, which symbolise perspectives, we pick via clustering.
- What plots visualize to show the design and operation of the REC.

4.3.1. Pareto Front Formulation

In energy system models (ESMs) with multiple objectives, it is essential to account for the varying scales of the objectives being optimised. Multi-objective optimization (MO) methods, such as the weighted sum approach, combine conflicting objectives into a single objective function by assigning weights based on their relative importance (Finke et al., 2024). However, objectives like monetary costs, CO2 emissions, and transformer congestion have different magnitudes, making it challenging to balance them.

Without compensatory weights, optimization results may be skewed or insensitive to certain objectives. Finke et al. (2024) highlight the necessity of considering the magnitude of each objective when assigning weights. To correct for these scale differences, we used a method where base weights were initially set equally to [1, 1, 1] across the three objectives. We then calculated relative importance by examining the total annual costs[1] associated with each objective, ensuring a balance by normalizing the weights so that their sum equals 1. This normalization corrects for the magnitude

[1] Using the average cost per flow factor yields similar results but does not take design into account.

imbalance, preventing smaller-scale objectives from dominating the optimization process. The resulting base weight factors are given in Table 2.

Table 2: Base weights for the Energy Trilemma objectives.

Parameter	Annual costs	Base weight factor
Monetary	12268.10	0.65
CO_2	47924.85	0.17
TCI	44763.59	0.18

We then used the Dirichlet distribution to generate diverse weight combinations. This distribution skews the weights toward the base weights while ensuring that the weight variations are proportional to their respective magnitudes. The Dirichlet method prevents clustering in unrealistic extremes and rather focuses the exploration on the established base weights, which compensate for the different objective magnitudes. We ran the model 500 times with different weight combinations to maintain a practical computational load while thoroughly exploring the solution space.

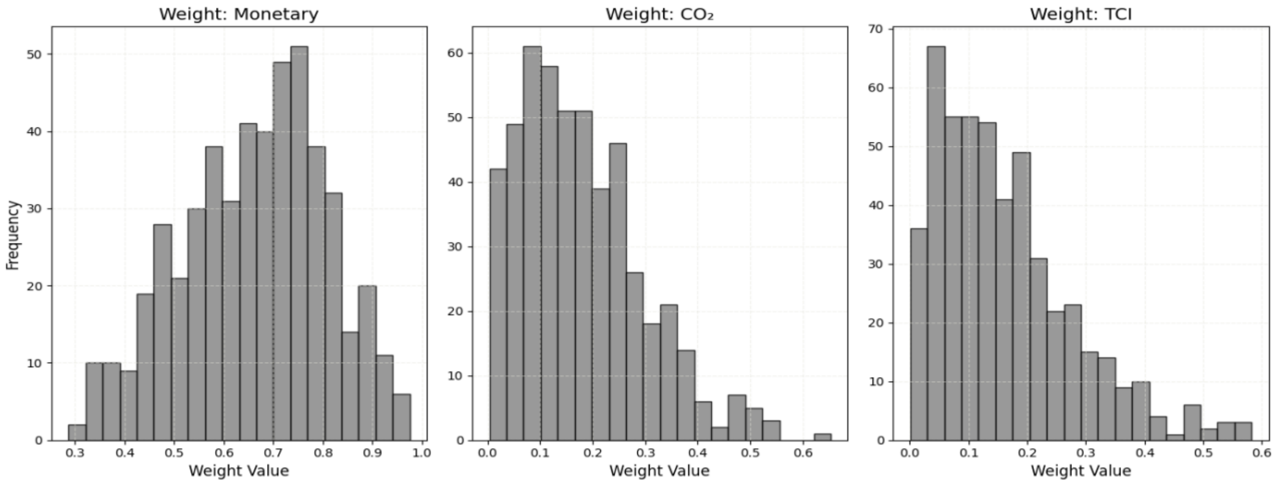

Figure 13: Weight distribution to form a Pareto front.

As the weight distribution introduces a bias in the system, we have included an additional analysis of the results under a uniform weight distribution in Appendix D.1. The alternate approach results in similar but more extreme results, supporting our choice to skew the weights.

4.3.2. Clustering to Obtain Scenarios

The Pareto fronts generated by multi-objective (MO) optimization provide a comprehensive view of solutions that are all equally optimal, representing different trade-offs between the objectives. However, the equal optimality makes it hard to analyse the scenarios in depth. This challenge can be addressed by recognizing that the importance of the objectives may vary in different contexts. In our analysis, we aim to show the trade-offs that occur when certain objectives (e.g., minimizing cost, reducing CO_2 emissions, or minimizing transformer congestion) are prioritised.

Instead of arbitrarily selecting solutions from the Pareto front, we cluster the solutions to create groups of similar ones, which enables us to select representative scenarios for further evaluation. Clustering is especially useful when there are many equally optimal solutions in a multi-objective optimization problem, as it reveals areas of the Pareto front where the trade-offs between objectives are the most pronounced. By selecting representative solutions from each cluster, we can ensure that the diversity of the Pareto front is well represented in the scenarios chosen for further analysis.

Our clustering process is carried out in several steps to ensure transparency and effective selection of representative solutions:

1. Data Selection and Preparation

Key metrics from the Pareto front results are extracted, focusing on three objectives: monetary cost, CO_2 emissions, and transformer congestion. These metrics reflect the trade-offs between affordability, sustainability, and grid security and serve as the basis for clustering.

2. Normalization of Metrics

To ensure equal weighting of all objectives, we normalize the selected metrics using MinMax scaling, transforming them into a range of 0 to 1. This prevents objectives with larger numerical ranges from dominating the clustering process.

3. Selecting the Optimal Number of Clusters

Before applying a clustering algorithm, we determine the optimal number of clusters using two methods:

- The Elbow Method: This method analyses the sum of squared distances within clusters as a function of the number of clusters. The optimal number of clusters is identified at the “elbow” point, where adding more clusters provides diminishing improvements in within-cluster variance reduction.
- The Silhouette Score: This method evaluates the compactness and separation of clusters, measuring how similar a point is to its assigned cluster compared to other clusters. A higher silhouette score indicates a better-defined clustering structure, helping validate the number of clusters selected.

4. Clustering with K-Means

Using the normalized metrics, we apply the K-Means algorithm to group solutions into clusters. K-Means clustering groups solutions by identifying K representative clusters based on their similarity in trade-offs between affordability, sustainability, and grid security. The algorithm starts by selecting K initial cluster centroids (as identified via the Elbow Method and Silhouette Score) and then assigns each solution to the nearest centroid based on its objective values. After assignment, the centroids are recalculated as the average of all points in their cluster, and the process repeats until the centroids stabilize. This ensures that each solution belongs to the cluster where it is most similar to others in terms of trade-offs (Canizes et al., 2023).

K-Means is chosen because it efficiently identifies structured trade-off patterns in the Pareto front, making it well-suited for this analysis. Other methods, such as hierarchical clustering, become computationally expensive for large datasets, while density-based approaches like DBSCAN work better for irregularly shaped clusters (Canizes et al., 2023).

5. Calculation of Average Weights and Costs

For each cluster, the centroid is identified as the representative solution, serving as the central point of the cluster in terms of the normalized objectives. By backtracking the weights corresponding to each centroid, we determine the multi-objective (MO) weight distribution that characterizes each region of the Pareto front. This process provides a clear understanding of the trade-offs between affordability, sustainability, and grid security between each cluster.

It is important to note that this approach does not explore the full solution space. Instead, it focuses on representative solutions, offering a simplified but interpretable view of the trade-offs. While the centroids do not capture all possible variations within the clusters, they provide a practical and meaningful summary of the system's behaviour. This method prioritizes clarity and interpretability over exhaustive exploration, ensuring that the results remain actionable and aligned with the energy trilemma framework.

In Appendix D.2, we explore a second method for clustering based on design, and operational variables, specifically focusing on flow caps and flow in/out behaviour. This approach shifts the clustering focus away from the normalized objectives (monetary costs, CO_2 emissions, and transformer congestion) and instead emphasizes extreme design and operational strategies. While these clusters capture unique characteristics of the system, they lack alignment with the energy trilemma dimensions. This makes them less intuitive and harder to interpret for practical decision-making. The clusters emphasize extremes rather than balanced trade-offs, which complicates their applicability for stakeholders seeking actionable insights, which is why we chose the method described in this section.

4.3.3. Analysis of the Results

First, we will plot the design-related parameters in a bar chart for each representative scenario. These parameters are the amount of PV and BESS installed. This data is obtained by looking at the flow_cap over the E1, E2 and transformer nodes. The results are plotted in a stacked bar chart.

To effectively illustrate the operational behaviour of the energy system, we present the results for two representative weeks: one in summer (August) and one in winter (February). Visualizing typical weeks instead of an entire year allows us to avoid cluttered and overly complex graphs, enabling clearer insights into system dynamics under different seasonal conditions. These weeks have been selected because they capture the seasonal variability in both solar generation patterns and price signals, two key drivers of system operation.

During summer, longer daylight hours result in increased solar energy generation, while winter conditions are characterized by reduced solar output and potentially higher energy demand as observed in Figure 14.

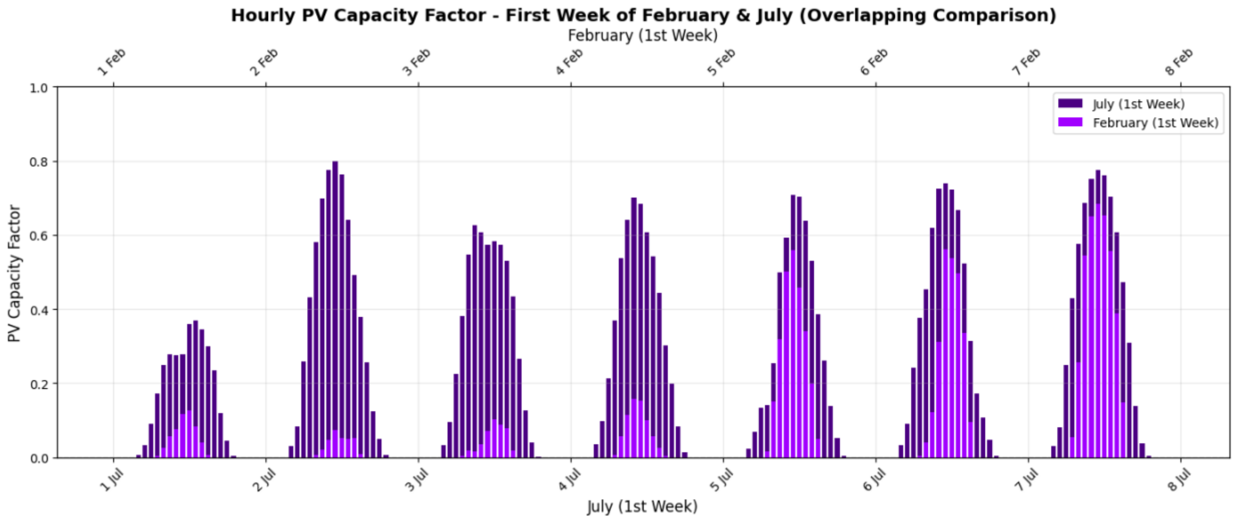

Figure 14: Solar Power capacity factor in a winter and summer week.

Additionally, we observe in Figure 15 that during summer, day-ahead prices are typically lower, and can even become negative.

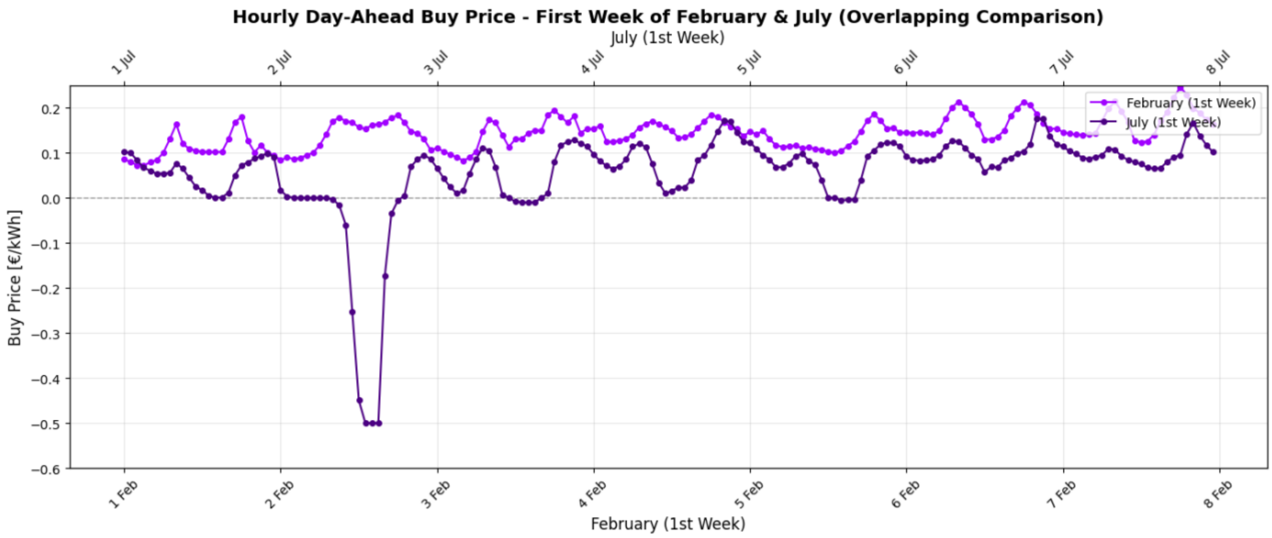

Figure 15: Hourly Day-ahead price in a winter and summer week.

The selected weeks provide a concise yet representative overview of the system's behaviour across varying external conditions. We will use these weeks to show the hourly operation of the LV system. Here, we can observe how the PV, Battery and Grid interactions are operated in different scenarios.

To complement the weekly operational analysis, we conclude each analysis section with load duration curves for key technologies. These load duration curves plot the sorted power output over a year, providing a clear visualization of its utilization patterns and contribution to overall system performance. These curves are particularly useful for identifying trends, peak contributions, and seasonal dependencies. We will use the same operational parameters for this.

By combining weekly visualizations with yearly load duration curves, we ensure both granularity and comprehensiveness in presenting the operational behaviour of the system.

4.4. Phase 4: Usage

In Phase 3, we illustrate trade-offs arising from diverse stakeholder perspectives, showing how differing priorities can lead to varying optimal design and operational outcomes. Building on this, we recognize that energy systems are inherently complex and deeply uncertain, with uncertainties stemming from structural assumptions, parametric variations, and conflicting stakeholder objectives (DeCarolis et al., 2016; Yue et al., 2018). Therefore, we deploy a sensitivity analysis to probe the solution space. The primary aim is to understand system behaviour under varying conditions and identify key dynamics, trade-offs, and sensitivities. In this section, we describe how the sensitivity analysis is conducted.

4.4.1. Type of Sensitivity Analysis

Global Sensitivity Analysis (GSA) is widely regarded as the most thorough method for evaluating how changes in parameters impact model outputs, as it considers the entire range of variability and interdependencies among parameters (Usher, 2015). Despite its comprehensiveness, GSA is computationally intensive, particularly for complex energy models like those used in this study. The inclusion of detailed temporal and spatial dimensions significantly increases the computational burden. As the number of parameters grows, the required simulations scale exponentially, making GSA resource-intensive (DeCarolis et al., 2016; Yue et al., 2018).

To balance comprehensiveness and feasibility, this study employs the One-at-a-Time (OAT) Sensitivity Analysis approach. OAT simplifies the evaluation process by isolating the impact of individual parameter changes while holding other variables constant at baseline values. This method significantly reduces computational requirements and enhances the clarity of the results by directly attributing changes in output to specific parameter variations. However, OAT does not capture interactions between parameters, a known limitation that should be considered when interpreting the results (DeCarolis et al., 2016; Usher, 2015; Yue et al., 2018).

This study conducts both structural and parametric sensitivity analyses using the OAT method. Structural sensitivity analysis examines how system parameters design influences outcomes, ensuring the model’s consistency across various configurations. Parametric sensitivity analysis assesses the effects of changes in numerical inputs (e.g. costs and demand profiles) on the design and operation of the energy system. This dual approach aids in the understanding of the model’s behaviour and identifying critical parameters and dependencies.

Together, these analyses probe the solution space, offering insights into system dynamics and uncovering robust strategies. This approach ensures the results remain transparent (DeCarolis et al., 2016; Usher, 2015; Yue et al., 2018).

4.4.2. Parameter Selection

Given the complexity and scale of our energy community model, we must carefully select parameters that are both uncertain (i.e. where precise values are difficult to determine) and sensitive (i.e. where small changes significantly impact results). This approach ensures computational efficiency and meaningful insights while avoiding unnecessary simulations.

Each parameter was assessed based on expert judgment on the criteria above. The results of this analysis are found in F. The identified parameters that exhibit both high uncertainty and high sensitivity are summarized in Table 3.

Table 3 Selected parameters for the sensitivity analysis.

Parameter	*Sensitivity Type*	*Reason for Selection*
Amount of Solar Power installed.	Structural Sensitivity	Urban variability in roof availability impacts renewable integration.
Amount of Battery (MV and LV) installed.	Structural Sensitivity	Structural sizing of battery capacity directly impacts system operation.
Weights (Objective Prioritization)	Parameter Sensitivity	Reflects stakeholder priorities and drives extreme scenario outcomes.
Transformer Size	Parameter Sensitivity	Highly location-dependent and strongly affects grid congestion.
Grid Power Cost and Revenues	Parameter Sensitivity	High variability across retail contracts and the implemented day-ahead market.
Electricity Demand	Parameter Sensitivity	Future consumption patterns are uncertain but impactful, especially with electrification trends.
Battery (MV and LV) Price	Parameter Sensitivity	Expected price reductions could drastically alter system Design.
Solar Power Price	Parameter Sensitivity	Expected price reductions could drastically alter system Design.

The selected parameters will be systematically varied using a one-at-a-time (OAT) Sensitivity Analysis approach. Each parameter was varied across a range that reflects either realistic bounds (e.g., market conditions or technological limitations) or hypothetical extremes (to stress-test the model). The specific values and ranges used for each parameter were selected based on a combination of literature review, expert judgment, and practical considerations. The ranges and reasoning behind them are found in Appendix G.

4.4.3. Analysis of the Results

The sensitivity analysis results are divided into structural and parameter sensitivity to evaluate their respective impacts on system design and operation. Structural sensitivity focuses on variations in key design variables such as solar PV capacity and battery size to examine how different configurations influence the system’s outcomes. Parameter sensitivity evaluates changes in critical numerical inputs, such as grid power prices and transformer capacities, to assess how operational outcomes respond to these uncertainties. This distinction allows for a clear assessment of the robustness of the results presented earlier.

To contextualize the sensitivity results, all scenarios are overlaid onto the identified Pareto front. Scenarios falling within the bounds of the Pareto front are considered consistent with the optimal trade-offs already established, requiring no further analysis. Scenarios representing extreme and implausible conditions are excluded from further consideration. For scenarios outside the Pareto front that appear relevant, the model is rerun with the specific overrides to verify whether deviations in the results are significant enough to influence the conclusions.

Thereafter, for both structural and parameter sensitivity, the analysis evaluates changes in design and operational variables. Design variables, such as solar PV and battery capacities, are examined to assess shifts in system configuration under different assumptions. Operational variables, including curtailment, grid imports and exports, and unmet demand, are analysed to evaluate the adaptability of the system's operation under varying conditions. We do this via violin plots. These charts show the variation of system design/operation in height, and the occurrence of the variation in width. This approach ensures a comprehensive understanding of how the system responds to uncertainties, thereby addressing the robustness of the findings.

The results of this analysis are used to validate the results from the base model. This process helps in answering sub-question 3 by ensuring the conclusions remain valid across a wide range of structural and parametric conditions.

5. Results

This chapter presents the findings from the optimization model, structured in sections to address key aspects of Renewable Energy Communities (RECs) design and operation. First, Pareto Fronts illustrate trade-offs between affordability, sustainability, and grid security. Next, Clusters group Pareto-optimal solutions to identify representative scenarios. The Design and Operation subsections describe design and operation per identified scenario. Finally, the structural and parametrical sensitivity analysis sections evaluate the robustness of results. The results are used to answer sub question 3.

5.1. Pareto Front

To visualize the Pareto fronts, the results are plotted in a three-dimensional space in Figure 16, where the axis corresponds to the primary cost objectives. Note that we have standardised the transformer congestion indicator between 0 and 1, as the exact size is non-dimensional and thus hard to interpret.

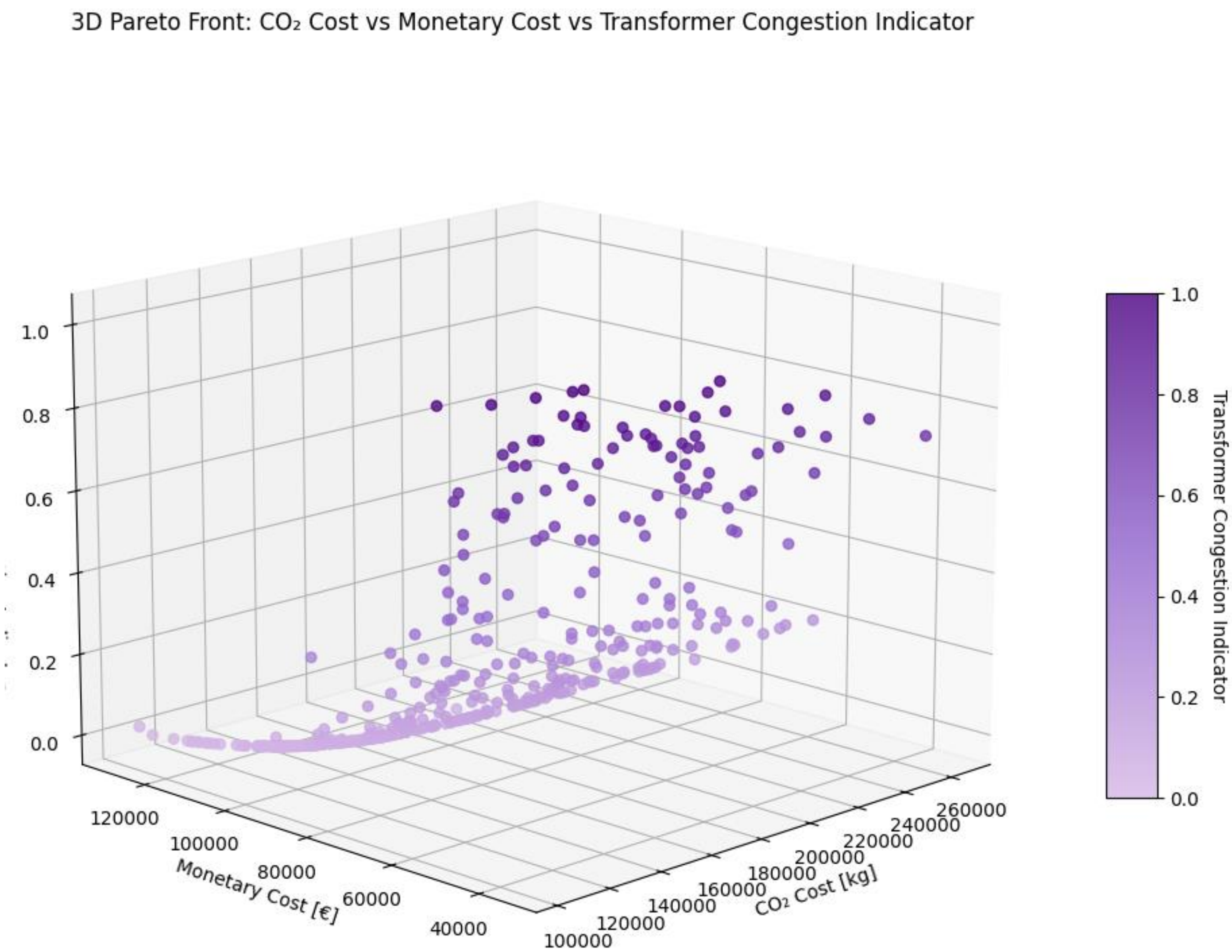

Figure 16 Three-dimensional Pareto front of the Energy Trilemma dimensions.

The relationships between monetary cost, CO_2 emissions, and transformer congestion indicators reveal distinct trade-off patterns across the analysed scenarios. In the 3D Pareto plot, these interdependencies converge into a curved surface, emphasizing the multi-dimensional nature of the trade-offs. The surface reveals clusters of scenarios where balanced trade-offs between cost, emissions, and congestion can be achieved. Extreme scenarios, whether prioritizing monetary costs, emissions, or congestion, are positioned along the plot's edges, underscoring the inherent tensions between these objectives. The visualization emphasizes that there is no single universally optimal scenario but rather a spectrum of possible solutions, each reflecting a different balance between affordability, sustainability, and grid security.

An inverse relationship is evident between monetary costs and CO_2 emissions in Figure 17. Scenarios with lower CO_2 emissions typically correspond to higher monetary costs, while scenarios with lower monetary costs tend to show increased CO_2 emissions. However, this trend is not strictly linear. Specific clusters indicate regions where moderate trade-offs exist, suggesting opportunities to achieve reasonable CO_2 reductions without disproportionately high costs.

A parabolic trend emerges when comparing monetary costs with TCI in Figure 18. Scenarios with extremely low monetary costs correspond to higher congestion penalties, signalling heavy grid reliance or bad timing of grid interactions. Conversely, scenarios with minimal congestion penalties often incur significantly higher monetary costs. Notably, a middle range of monetary costs aligns with relatively low congestion indicators, indicating balanced trade-offs.

The relationship between CO_2 emissions and TCI display a scattered but nuanced pattern in Figure 19. We observe no scenarios with high TCI and CO_2, indicating the model works as intended as grid imports are tied to CO_2 costs. Additionally, we can observe a pattern where an increase in TCI cost leads to an increase in CO_2 cost. However, this does not hold true for all scenarios. Here, we observe that the timing of the grid interaction can affect the transformer congestion indicator, whilst not impacting the CO_2 emissions. This is because the TCI is time dependent whilst the CO_2 cost factor is a static measure of grid usage. This highlights the importance of the distinction between design and operation in this thesis.

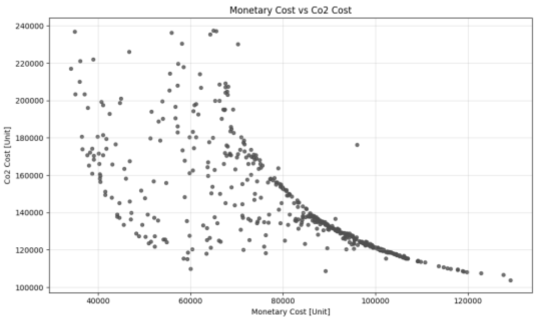

Figure 17: Pareto front of Monetary cost versus CO_2 emissions.

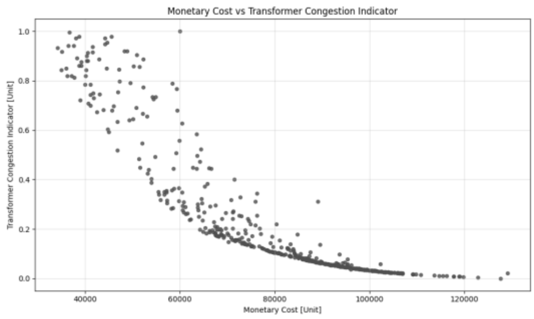

Figure 18: Pareto front of Monetary cost versus the TCI.

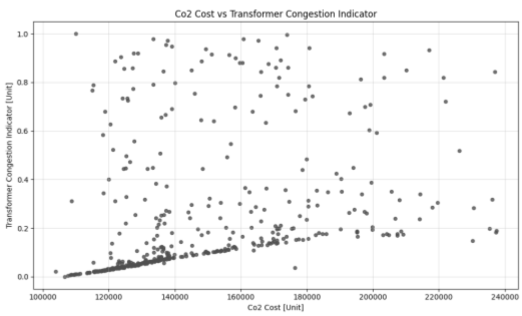

Figure 19: Pareto front of the TCI versus CO_2 emissions.

5.2. Clusters

By applying the K-means clustering algorithm to the scaled data, four distinct clusters were identified. The optimal number of clusters was determined using the Elbow Method (Figure 20) and Silhouette Score (Figure 21). While three clusters achieve the highest silhouette score, the addition of a fourth cluster captures more nuanced trade-offs between affordability, sustainability, and grid security without compromising cluster distinctiveness significantly. This is important for the study's objective, as the fourth cluster introduces configurations that highlight specific interactions between the energy trilemma dimensions, providing additional insights into the trade-offs. Therefore, we proceed with four clusters.

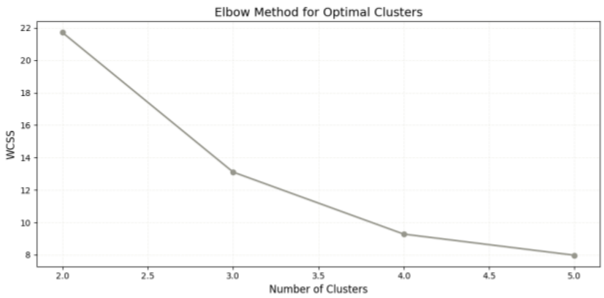

Figure 20: Elbow method for the optimal number of clusters.

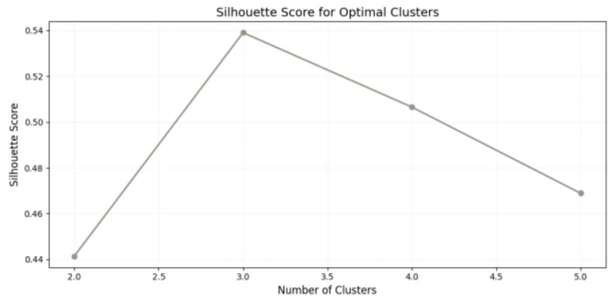

Figure 21: Silhouette score for the optimal number of clusters.

The results of the clustering analysis are presented using a two-dimensional Pareto front visualization. The Pareto front in Figure 22 is colour-coded to highlight the four clusters, and representative scenarios are marked with yellow markers to indicate the centroid of each cluster. We observe that the clusters represent large solution spaces, the centroids are, therefore, illustrative but not exhaustive to the results that could be identified from this analysis.

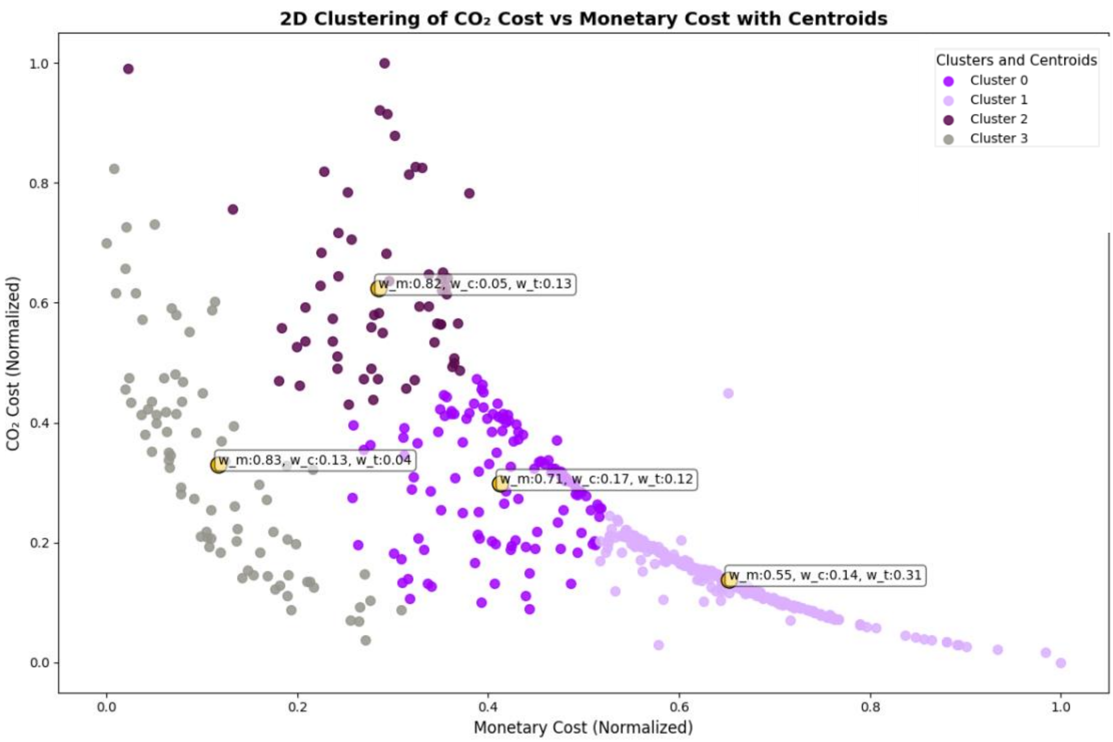

Figure 22: Two-dimensional Pareto Front with coloured cluster visualization.

The plot is presented in two dimensions, focusing on monetary costs and CO_2 emissions, simplifying the visualization while slightly diminishing the interpretability of the third dimension, grid security. Despite this limitation, the 2D representation provides a clear overview of the clusters, revealing distinct patterns that align with the energy trilemma dimensions: affordability, sustainability, and security.

Cluster 3 is positioned on the left side of the Pareto front and is characterized by minimal monetary costs, emphasizing affordability through low weights on CO_2 and TCI. The variability in CO_2 emissions within this cluster arises from differences in grid interactions, as grid transactions are statically tied to CO_2 emissions. Configurations with higher grid interaction levels exhibit increased emissions. These trade-offs highlight diverse design and operational strategies even within one cluster as the system tries to balance the three Trilemma objectives.

Cluster 2 is in the upper-middle region, representing a trade-off between affordability and grid security. These solutions emphasize reduced transformer strain while maintaining moderate monetary costs.

Cluster 1 appears near the centre of the Pareto front, reflecting a trade-off between affordability and sustainability. These scenarios achieve moderate monetary costs and low CO_2 emissions, though grid security is less emphasized. This cluster highlights configurations where reducing emissions and maintaining cost-efficiency are the primary objectives.

Cluster 0 is situated in the lower-right region, where CO_2 emissions and TCI values are minimised at the expense of higher monetary costs. This cluster represents a synergy between sustainability and grid security, demonstrating configurations that prioritize emissions reduction and grid stability over affordability.

Each cluster has a representative centroid, identified as described in section 3.6.2. We give the associated weights of the centroids in Table 4. These weight priorities may reflect varying stakeholder perspectives, however, due to time constraints of the thesis we are not able to couple actors to the perspectives. Note that the weights should be interpreted relative to the base weights identified in section 3.6.1. as they compensate for the magnitude differences between the Trilemma Pillars.

While the clustering provides meaningful insights into trade-offs between affordability, sustainability, and grid security, some overlap between clusters is observed. For example, Clusters 0 and 1 both emphasize sustainability but differ in their prioritization of affordability and grid security. This overlap reflects the inherent complexity of energy system design, where configurations do not align neatly with a single priority. Instead, these scenarios often address multiple objectives simultaneously, underscoring the challenges of balancing the energy trilemma.

The rationale for the cluster names in Table 4 is derived from the patterns observed in Figures 17–19. Cluster 3 focuses on affordability, which often conflicts with sustainability and grid security, as seen in the inverse relationship between monetary costs and CO_2 emissions or TCI. Clusters 2 and 1 highlight trade-offs where affordability is combined with one other objective, while deprioritizing the third. Finally, Cluster 0 demonstrates a synergy between sustainability and grid security, achieved at higher monetary costs.

Table 4: Representative centroid per cluster and the corresponding Trilemma pillar.

Cluster	**Name**	**Monetary Weight (w_m)**	**CO_2 Weight (w_{CO_2})**	**TCI Weight (w_{TCI})**
3	Affordable	0.83	0.13	0.04
2	Affordable and Secure	0.82	0.05	0.13
1	Affordable and Sustainable	0.71	0.17	0.12
0	Sustainable and Secure	0.55	0.14	0.31

5.3. Design

We show the installed capacity per scenario in Figure 23. In terms of design, we observe the following when comparing the scenarios.

Affordable

In the affordability scenario, the system prioritizes minimal monetary costs. High solar capacity (919 kW ensures cost-effective electricity generation, which may also allow for energy sales back to the grid. The inclusion of MV battery storage (137 kW), hints at a trading-strategy with the MV grid. The minimal LV battery capacity (15 kW) indicates a deprioritisation of localized grid security, as these batteries are normally focused on managing transformer congestion by offsetting grid interaction timing.

Affordable and Secure

The affordability-security scenario balances cost-efficiency with grid security. The low solar capacity (359 kW) reflects a strategic decision to reduce the amount of energy that could be sold back to the grid, as surplus energy would need to be curtailed if not stored or used locally. The modest LV battery capacity (44 kW) is designed to offset grid interactions during problematic times, helping to alleviate transformer congestion, but not to increase trade with the grid, explaining its low size. The inclusion of a small MV battery (13 kW) supports minimal trade options but is not a significant contributor to grid security. This design thus focuses on reducing transformer strain at a low cost, achieving a trade-off between affordability and security by minimizing investment costs while avoiding transformer load during peak times.

Affordable and Sustainable

The affordability-sustainability scenario emphasizes emissions reduction alongside cost-efficiency. The system includes high solar capacity (720 kW), which directly reduces reliance on grid imports and minimises CO_2 emissions. The substantial LV battery capacity (187 kW) supports balancing energy generation and consumption, reducing curtailment, and optimizing when energy is sold or bought from the grid. Notably, the absence of MV batteries aligns with the sustainability goal, as these batteries do not contribute to reducing PV curtailment. By leveraging solar energy and LV batteries, the system avoids high CO_2 emissions from grid interactions, balancing affordability and sustainability effectively, though grid security is deprioritized.

Sustainable and Secure

The sustainability-security scenario achieves a synergy between environmental and infrastructural priorities. The very high solar capacity (972 kW) ensures that a significant portion of the system's energy needs is met through renewable sources, minimizing CO_2 emissions. The inclusion of large LV battery storage (233 kW) supports the avoidance of PV curtailment and reduces reliance on grid imports during peak periods, enhancing grid stability. The absence of MV batteries reflects a focus on localized solutions, consistent with both sustainability and grid security goals. This design prioritizes self-sufficiency by using renewable generation and storage to ensure both environmental and grid stability objectives, though at higher monetary costs.

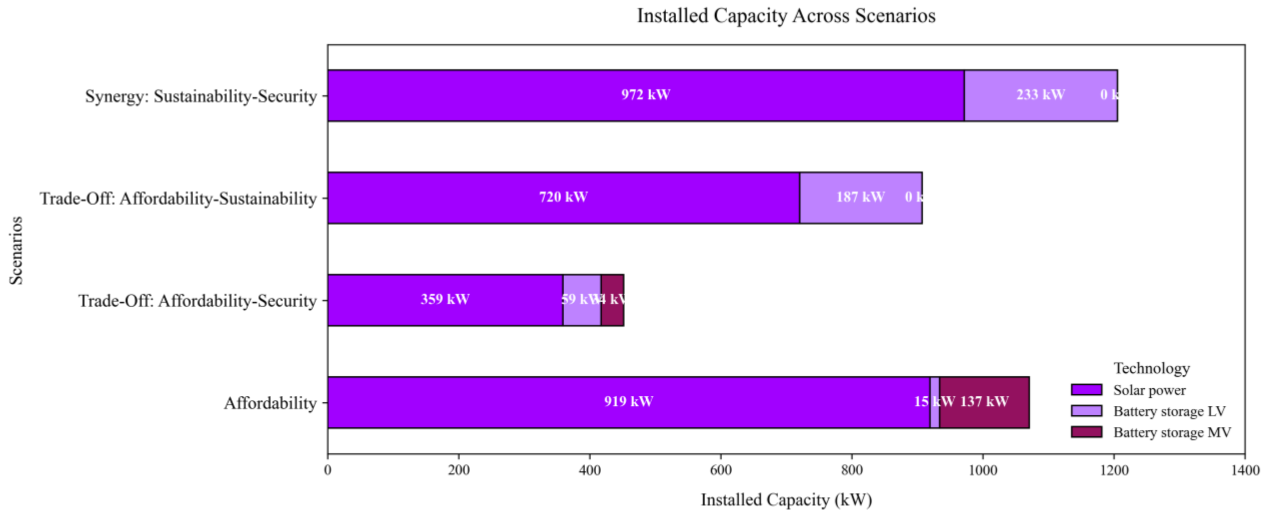

Figure 23: Installed capacities across scenarios.

5.4. Operation

The operation of Renewable Energy Community (REC) assets varies significantly across scenarios, reflecting distinct strategies driven by seasonal dynamics and varying priorities. Each scenario demonstrates unique patterns of grid interaction, battery utilization, and photovoltaic (PV) curtailment, influenced by the underlying objective weights. In this chapter we focus on the operation of LV grid. As supplementary material we include the interactions on the PV and MV level in Appendix E, to show the impact of the objective weights on the hourly curtailment and MV battery operation.

5.4.1. Scenario: Affordable

The Affordability scenario prioritizes minimizing operational costs by actively engaging in grid interactions and leveraging price arbitrage opportunities. This design is characterized by high grid reliance, limited battery storage usage, and a strong focus on economic optimization through market price dynamics.

During the winter, the energy system is dominated by grid imports due to limited solar availability. On sunny days, all generated solar energy is used for self-consumption, with any excess sold to the grid. There is minimal interaction with the battery, highlighting a lack of storage utilization to offset grid reliance or shift consumption patterns.

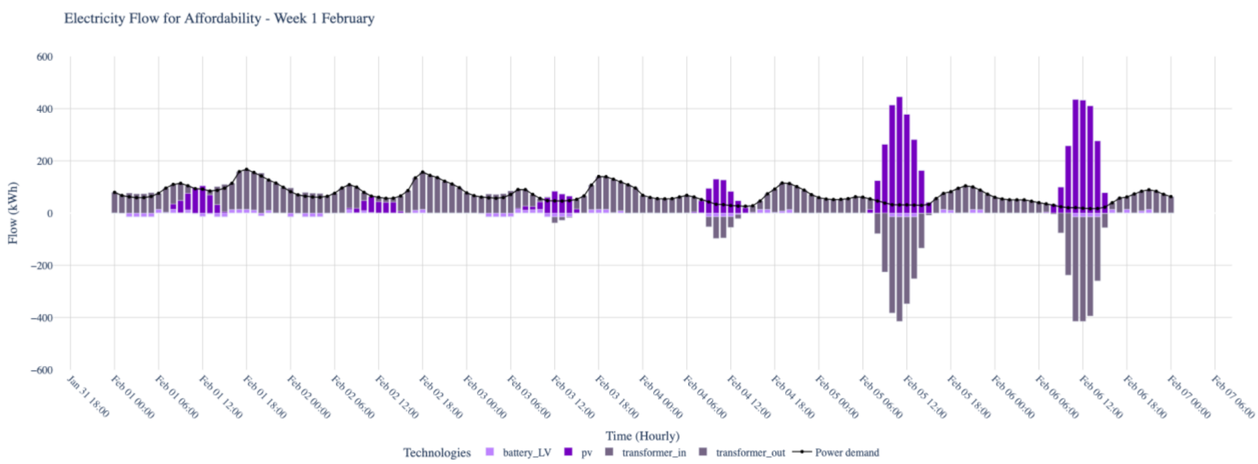

Figure 24: Electricity flow for the Affordable scenario in the first week of February.

In the summer, the system operates similarly to winter. Solar energy is fully utilized, and the excess is consistently sold to the grid. Batteries remain underutilized, with no evidence of load shifting or efforts to align consumption with solar generation. Most demand is met directly through grid imports.

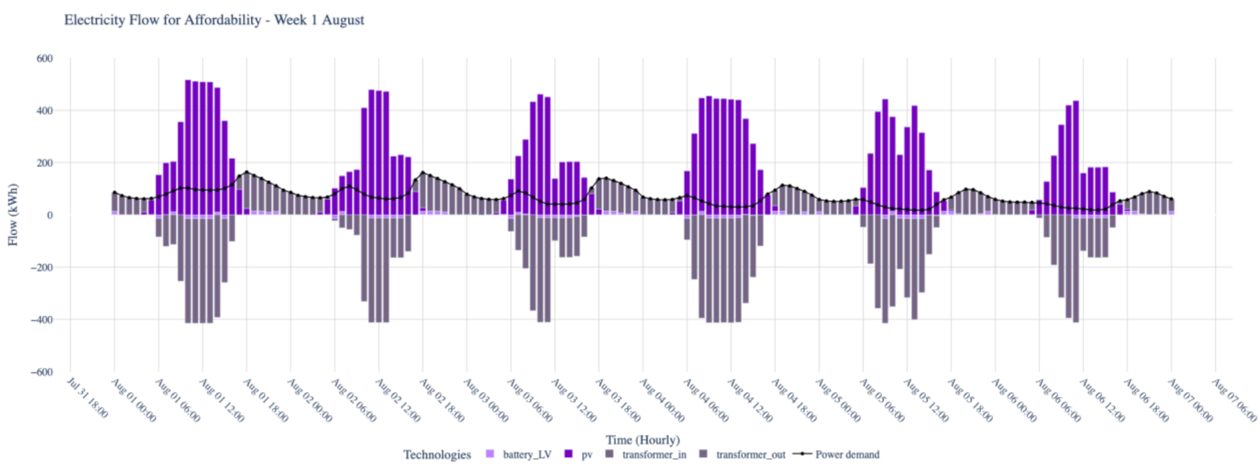

Figure 25: Electricity flow for the Affordable scenario in the first week of August.

The Affordable scenario is the only configuration that features significant MV battery capacity, which plays a key role in its operation, shown in Appendix E. In winter, the system purchases additional energy during periods of low electricity prices, storing it in MV batteries. This stored energy is discharged during high-price periods, such as mornings and evenings. Additionally, during periods of excess solar generation, the MV battery is used to store energy rather than exporting it immediately when grid prices are low. This energy is then sold later at higher prices, improving the economic performance of the system.

In summer, the system exhibits the same operational behaviour but on a larger scale due to increased solar availability. The MV battery ensures that excess electricity always has a storage destination, minimizing curtailment. However, this behaviour places significant strain on the transformer, particularly during periods of high export activity.

Annually, the system curtails only 19% of its solar generation by prioritizing grid transactions and leveraging MV batteries, often at the expense of grid security. The MV batteries operate at maximum capacity approximately half of the time they are in use and are actively utilized for a third of the year, highlighting their critical role in balancing supply and demand.

The load duration curve reveals the system's reliance on the transformer. The transformer out operates at maximum capacity for 10% of the year to accommodate solar exports, while the transformer in is used consistently at moderate capacity for two-thirds of the year. This operational pattern shows the system's heavy dependence on grid interactions and highlights potential congestion risks during peak solar export periods. The strategic use of MV batteries in this scenario effectively reduces curtailment and improves economic outcomes but introduces challenges for grid infrastructure.

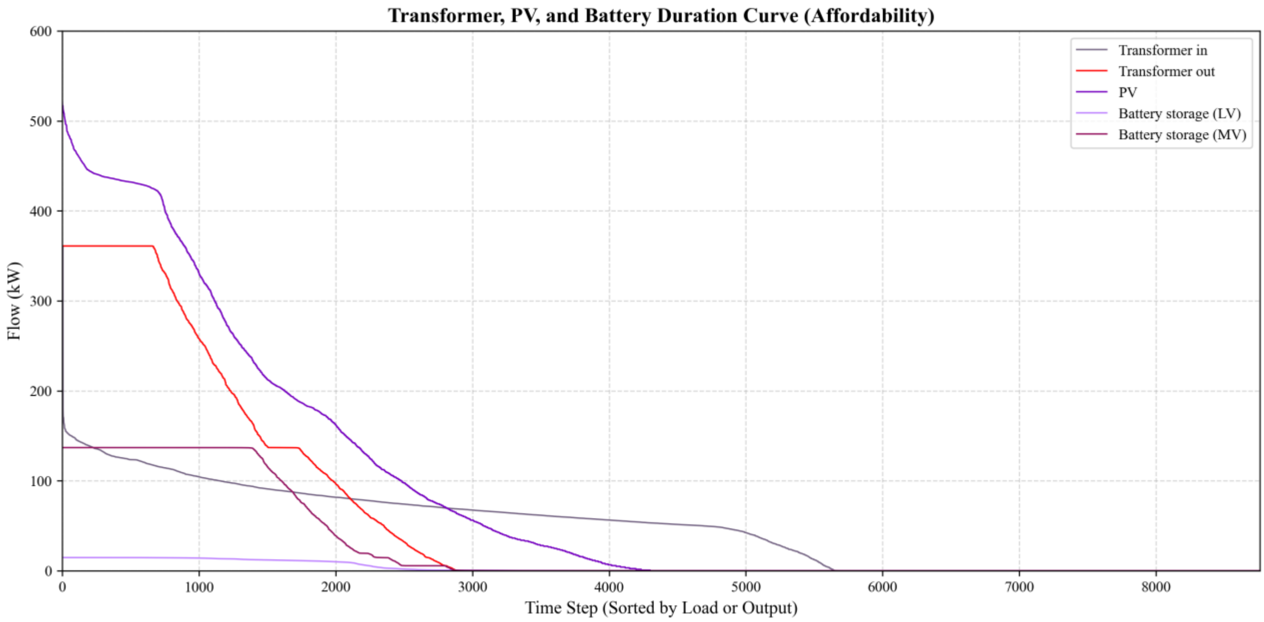

Figure 26: Load duration curves for the Affordable scenario.

5.4.2. Scenario: Affordable and Secure

The Affordable and Secure scenario prioritizes balancing cost-effectiveness with grid security. By optimizing the operation of batteries and solar assets, the scenario seeks to minimise transformer strain and curtailment.

In winter, the batteries charge during low-demand periods, such as at night or mid-day, and discharge during high-demand periods, typically in the morning and evening. This operation reduces strain on the transformer during periods of high congestion probability. The assets in this scenario are relatively small, as previously discussed, and most PV generation is used for self-consumption or stored for later use or sale. When solar generation exceeds the combined storage and consumption capacity, the excess electricity is sold to the grid.

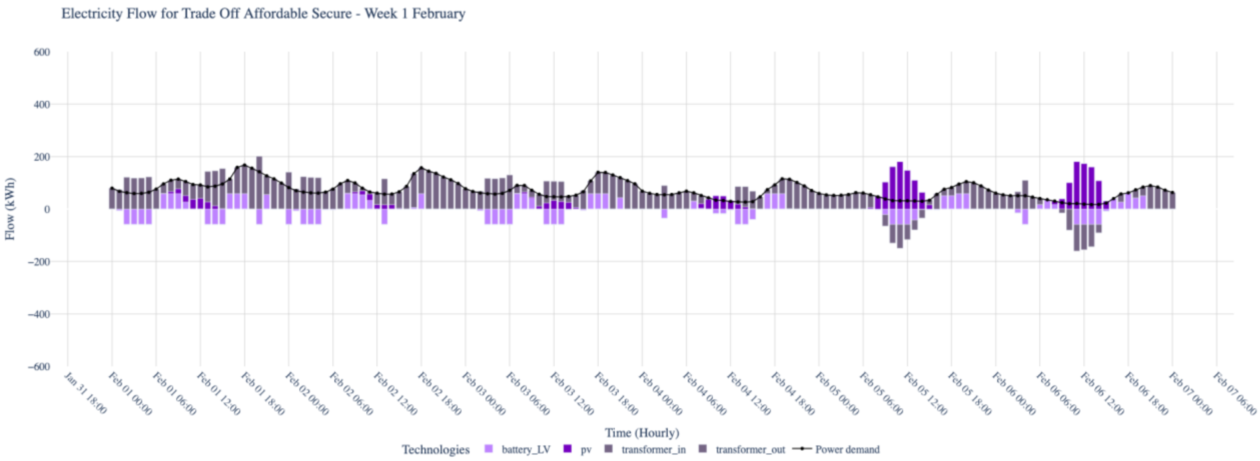

Figure 27: Electricity flow for the Affordable and Secure scenario in the first week of February.

A similar operational pattern is observed in summer, with most solar energy being used directly for consumption. Batteries charge during periods of high solar generation and discharge later to avoid grid interactions during congestion-prone times. Despite these efforts, a significant amount of curtailment occurs at the PV level due to the limited capacity of the system to store or consume all available solar power (Appendix E).

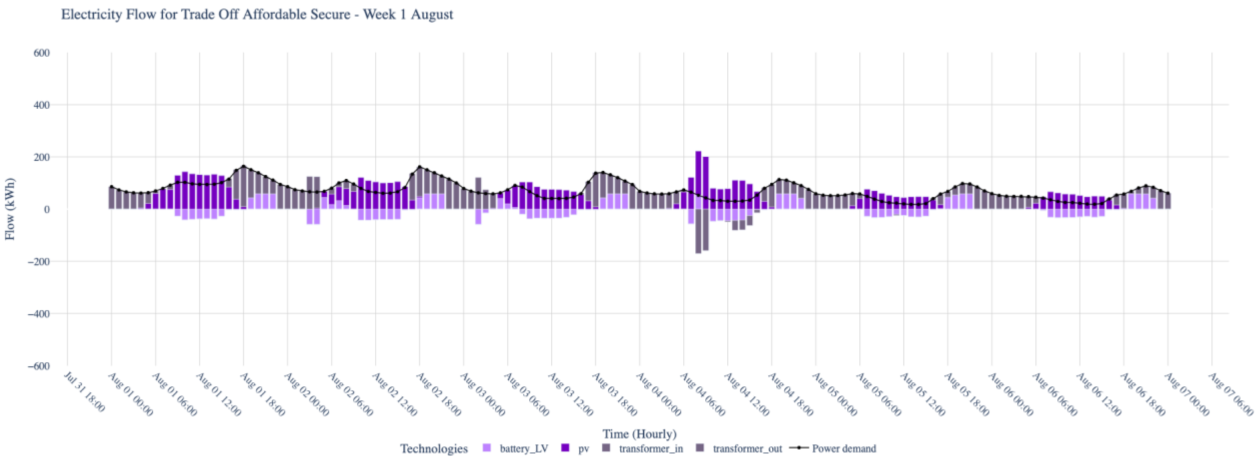

Figure 28: Electricity flow for the Affordable and Secure scenario in the first week of August.

The load duration curve indicates a high reliance on grid imports to meet demand. Selling behaviour is limited, occurring only during periods of extreme electricity prices, and remains well below the transformer's capacity. Battery utilization at both LV and MV levels is minimal and focused on storing energy for later consumption or performing small-scale arbitrage trading, neither of which significantly strain the transformer. Solar curtailment is moderate at 31%, reflecting the appropriately scaled PV capacity designed to meet demand without excessive oversizing. Most solar generation in this scenario is used for direct consumption, aligning with the objective of minimizing transformer strain and grid interactions.

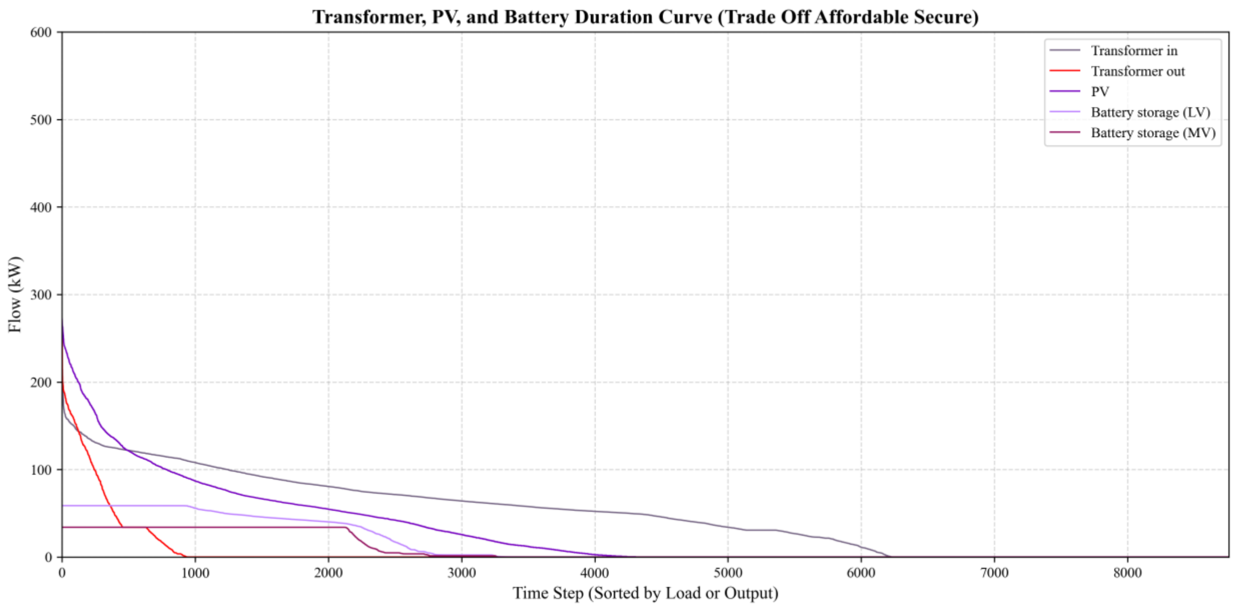

Figure 29: Load duration curves for the Affordable and Secure scenario

5.4.3. Scenario: Affordable and Sustainable

The Affordable and Sustainable scenario optimises energy use and sustainability while maintaining cost efficiency.

In winter, curtailment is minimal as solar power is used for consumption, charging batteries, or selling to the grid. During high solar hours, the PV system appears oversized, with excess generation beyond immediate demand or storage capacity, forcing the model to choose between selling or curtailing. In this scenario, we sell the excess energy. Furthermore, batteries are charged heavily during low electricity prices at night and discharged during morning peak demand. This pattern is occasionally repeated in the afternoon if PV generation is insufficient to charge the battery, though charging does not occur far in advance due to inefficiencies and discharge timing constraints.

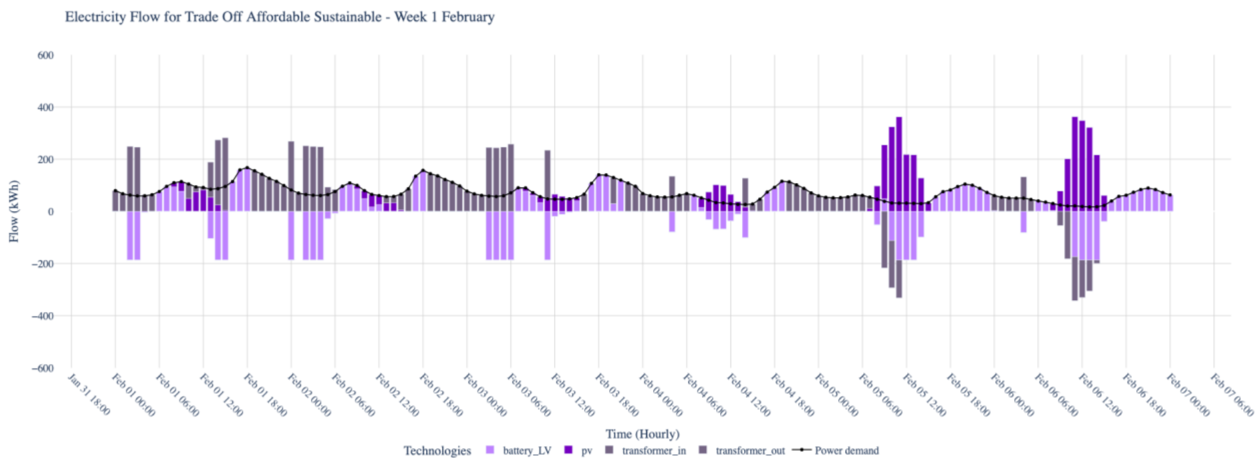

Figure 30: Electricity flow for the Affordable and Sustainable scenario in the first week of February.

In summer, curtailment becomes significant. Most PV energy is consumed directly or used to charge batteries, which are later discharged during high-price periods. However, the batteries are undersized for the summer PV output, leading to continued reliance on the grid. Batteries are not charged overnight due to unattractive electricity prices. Grid exports are limited and occur only during periods of extreme prices. The PV capacity is appropriately sized for winter demand but oversized for summer conditions, resulting in 36% annual curtailment.

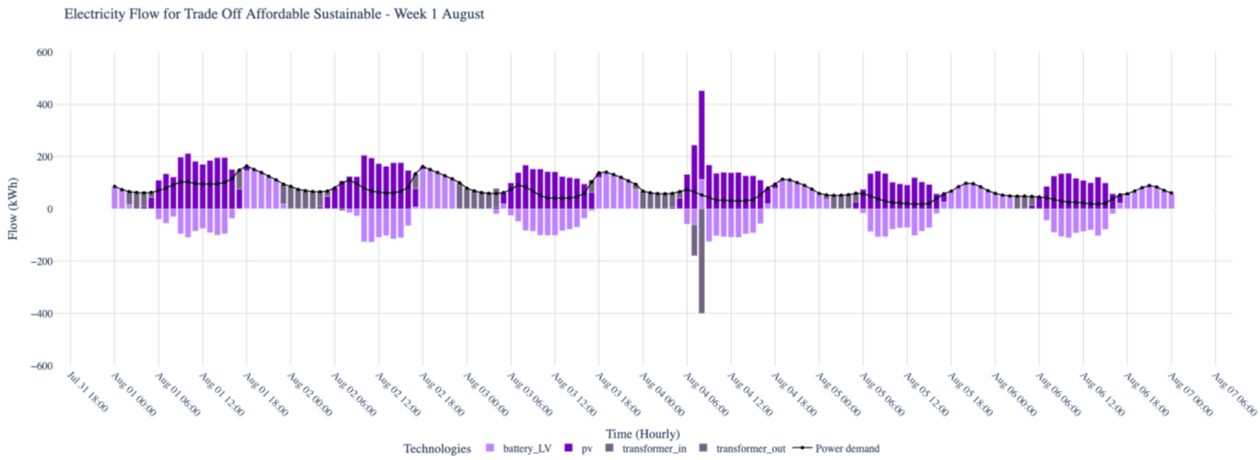

Figure 31: Electricity flow for the Affordable and Sustainable scenario in the first week of August.

The load duration curve highlights the large PV capacity and associated curtailment. This reveals a limitation in the model: CO_2 emissions are only associated with grid imports. There are no incentives tied to reducing national or medium-voltage grid CO_2 intensity through exports. As a result, curtailment persists, as the system is penalized for grid consumption but not rewarded for exporting surplus energy. Including such incentives could significantly alter the system's operation.

Lastly, the scenario features no medium-voltage batteries. Grid imports are limited to approximately one-third of the year. When energy is exported to the grid, it occurs during extreme price events, and the transformer operates at maximum capacity, as there are no restrictions on transformer usage in this scenario. The low-voltage battery operates at its maximum capacity most of the time and is used for about one-third of the year, reflecting its role in balancing supply and demand within its limitations.

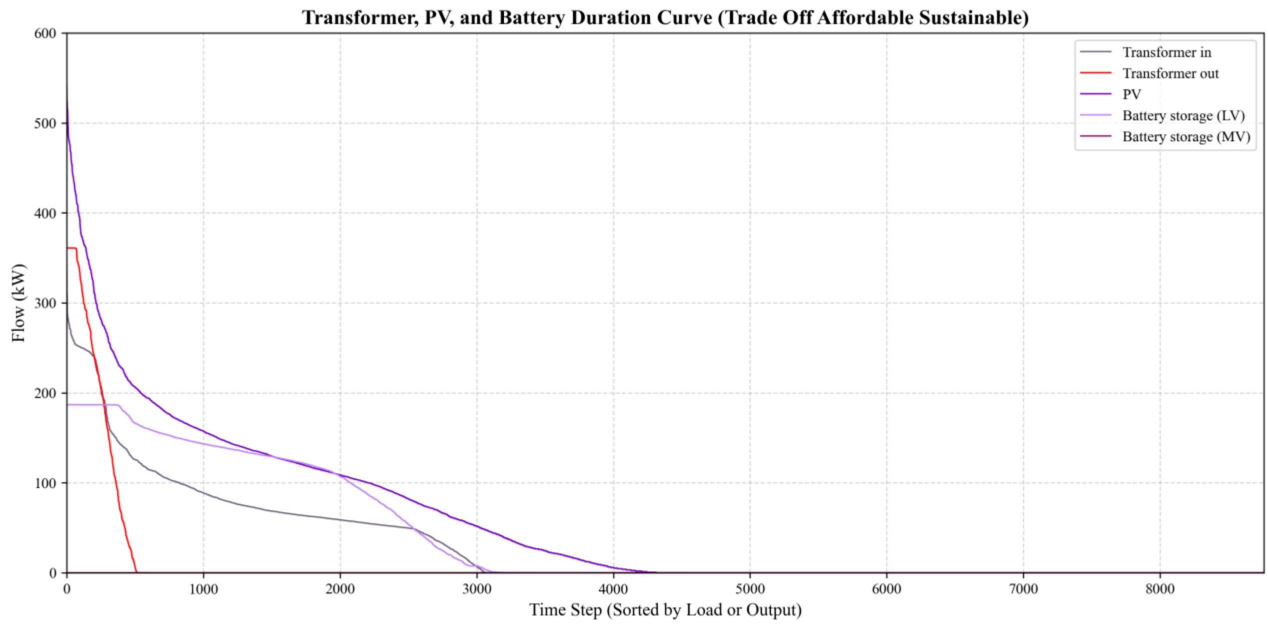

Figure 32: Load duration curves for the Affordable and Sustainable scenario.

5.4.4. Scenario: Sustainable and Secure

The Sustainable and Secure scenario prioritizes self-sufficiency

In winter, all PV generation is used for self-consumption. However, during periods of high solar generation and limited demand or storage capacity, significant curtailment occurs. The inability to export to the medium-voltage grid due to security constraints exacerbates this issue. Batteries are charged during low-price periods, such as at night, to provide energy for later use. There is no selling of electricity to the grid in this representative week.

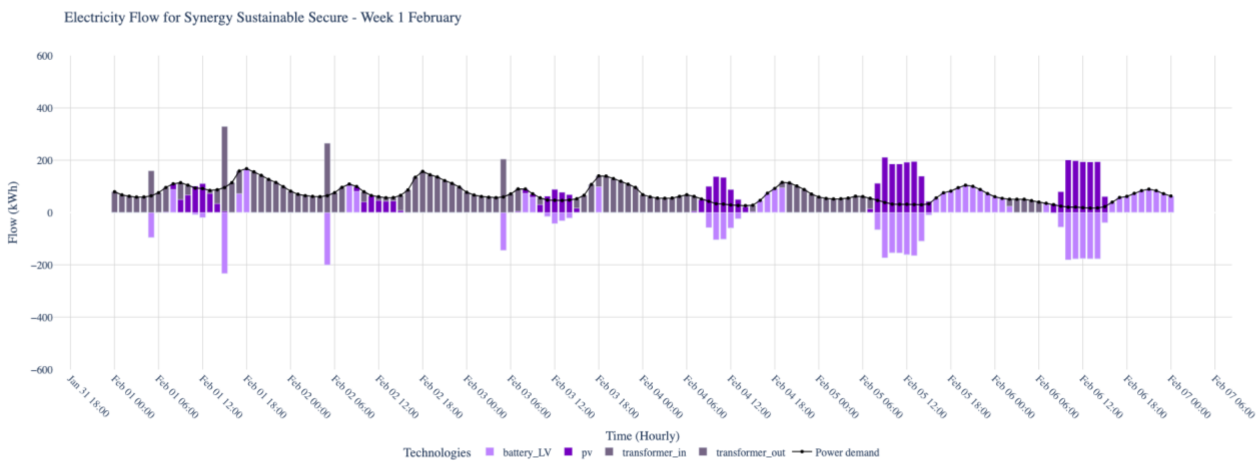

Figure 33: Electricity flow for the Sustainable and Secure scenario in the first week of February.

In summer, solar energy is utilized primarily to charge the batteries, which are later discharged to meet demand. Despite this, the battery flow capacity is insufficient to handle the large influx of solar energy, leading to high curtailment levels. Additionally, the limited battery capacity prevents sufficient energy storage to provide power through the night. With a discharge and charge flow cap of 0.25 per storage capacity, the battery can only charge or discharge at peak capacity for four hours, restricting its ability to optimise energy use over extended periods. While the scenario achieves a high degree of self-sufficiency, it falls short of full self-sufficiency due to these technical battery limitations. This leads to significant curtailment, as 56% of Solar Power is curtailed annually.

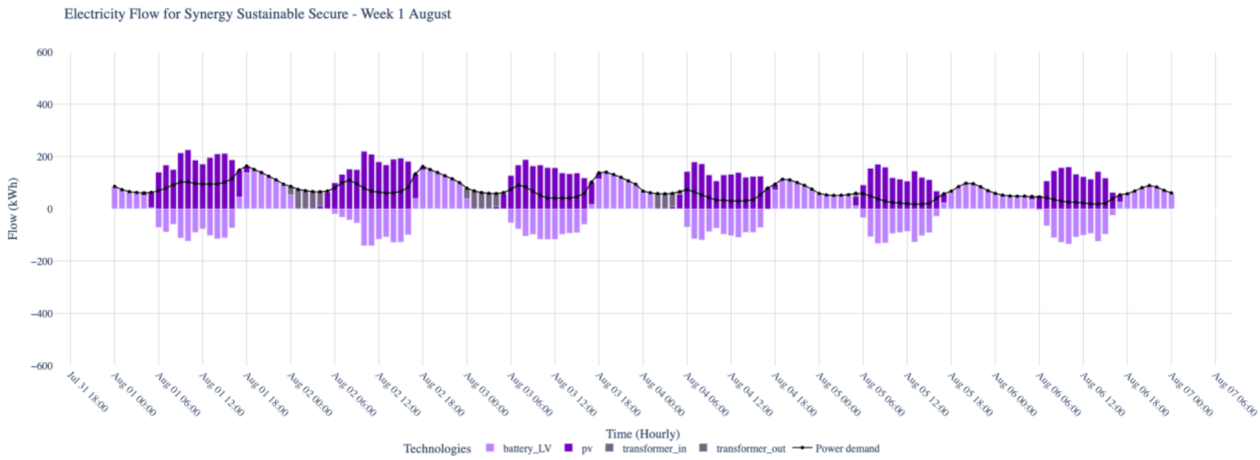

Figure 34: Electricity flow for the Sustainable and Secure scenario in the first week of August.

The load duration curve reveals no electricity is sold to the grid in this scenario. Nearly all PV generation is either consumed immediately or stored for later use, reflecting the system's focus on maximizing local energy use while avoiding grid interactions. However, the inability to fully utilize available solar energy highlights the challenges posed by storage and flow constraints.

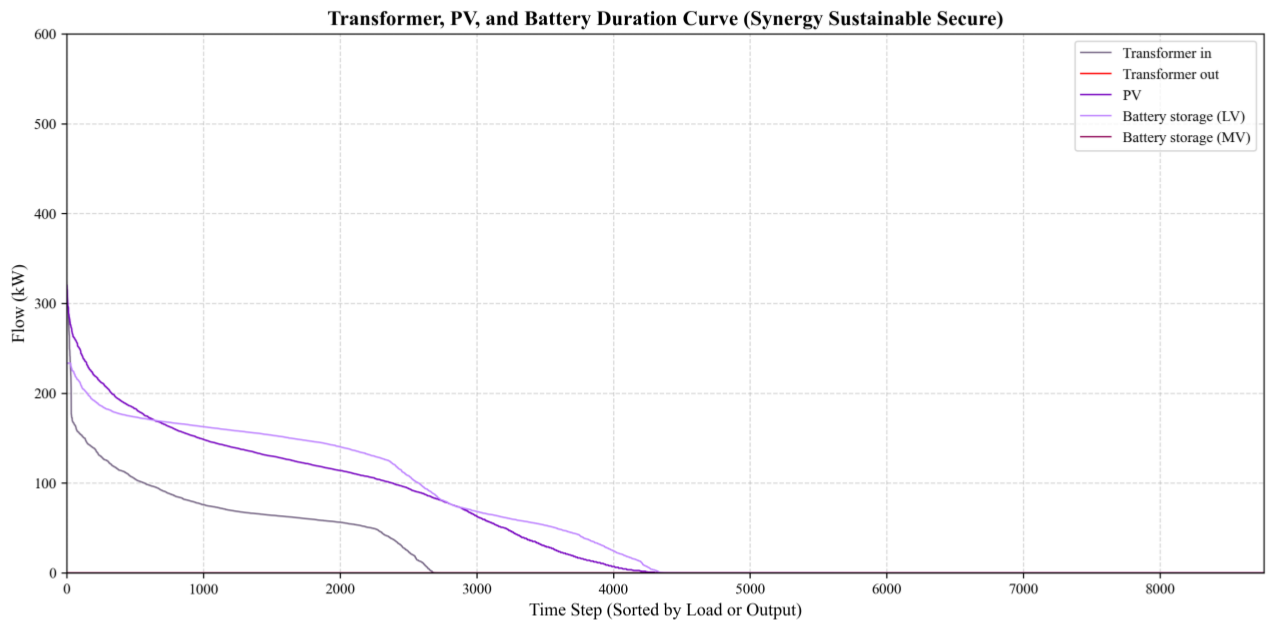

Figure 35: Load duration curves for the Sustainable and Secure scenario.

5.5. Structural Sensitivity Analysis

This section examines the effects of structural sensitivity on system performance by analysing key design and operational variables. The analysis focuses on how changes in Solar Power capacity, MV and LV battery storage influence curtailment, grid imports, and grid exports, providing insights into the interplay between system design and operational efficiency. We visualise how the sensitivity scenarios vary from the identified pareto front in figure 36.

In the identified model, we did not reach the maximum installable amount of Solar Power. However, decreasing Solar Power capacity is associated with a significant increase in CO_2 emissions due to an increase in grid imports. This result is like the result found in 5.4.1. Scenario Affordable.

The implementation of MV battery storage results in lower monetary costs and increased CO_2 emissions until 200 kW. Thereafter, the MV battery worsens all three dimensions of the Energy Trilemma. This can be attributed to high investment costs and limited operational benefits in terms of reducing grid dependency or improving self-sufficiency. The inefficiency of MV battery systems in the current scenarios highlights their limited applicability under the modelled system conditions as there are too little instances to trade with the MV grid in a profitable way.

The absence of any LV battery storage leads to substantially higher CO_2 costs, as the system becomes heavily reliant on grid electricity to meet demand and cannot store Solar Power effectively. Adding battery capacity reduces CO_2 costs by enabling a time shift in grid interactions and optimizing the use of renewable energy. Still, the batteries are not effective in lowering costs, as the removal of batteries results in lower system costs. Moreover, beyond a capacity of approximately 200 kW, the system exhibits diminishing returns in CO_2 reduction, while monetary costs rise sharply due to the high investment required for additional storage.

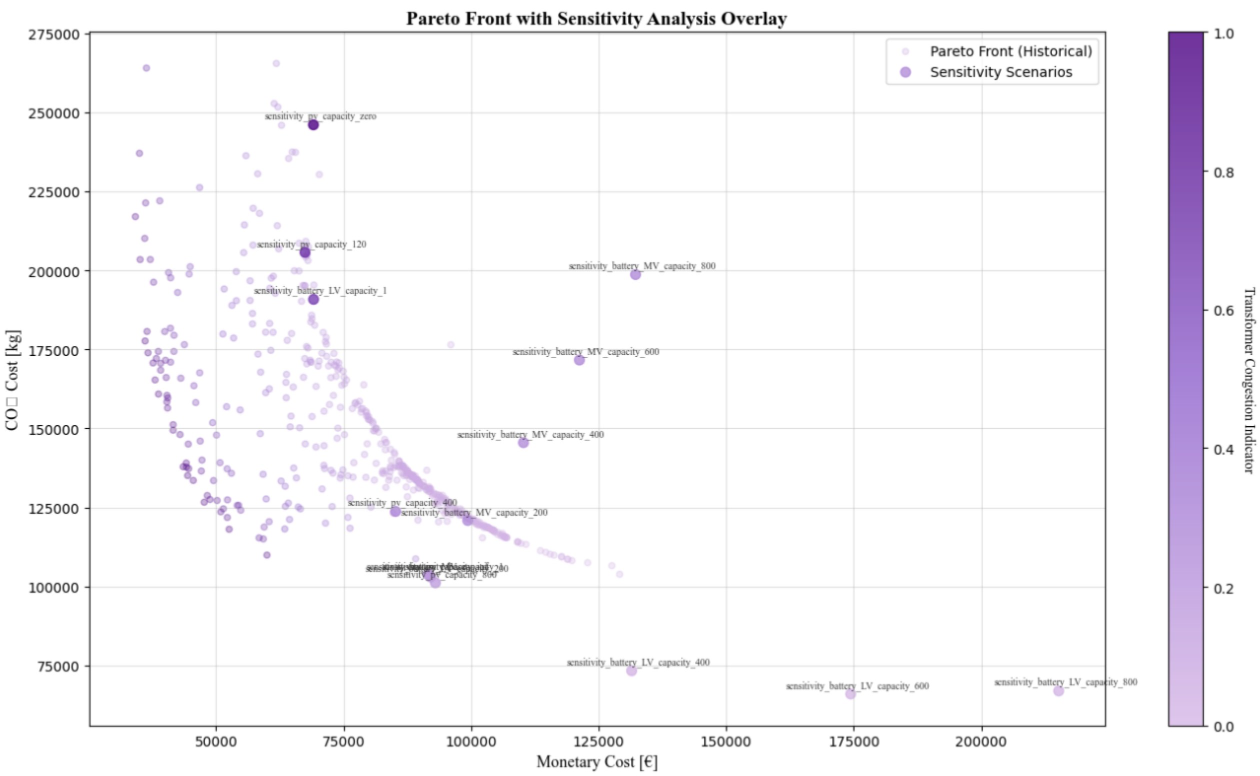

Figure 36: Structural sensitivity runs compared to the identified Pareto front.

The violin plot in Figure 37 illustrates the distribution of design variables from the structural sensitivity analysis, showing how manual alterations to the model's structure impact system design. The extended tails represent less efficient configurations forced by the sensitivity runs, leading to higher costs, as observed in Figure 36.

Notably, the wider regions near the median highlight configurations consistent with the optimal design outcomes identified in Section 5.3. This confirms the robustness of the results: even when the model is pushed beyond its originally defined optimal boundaries, the average outcomes remain aligned with the design analysis. This resilience to structural changes underscores the reliability of the proposed REC configurations.

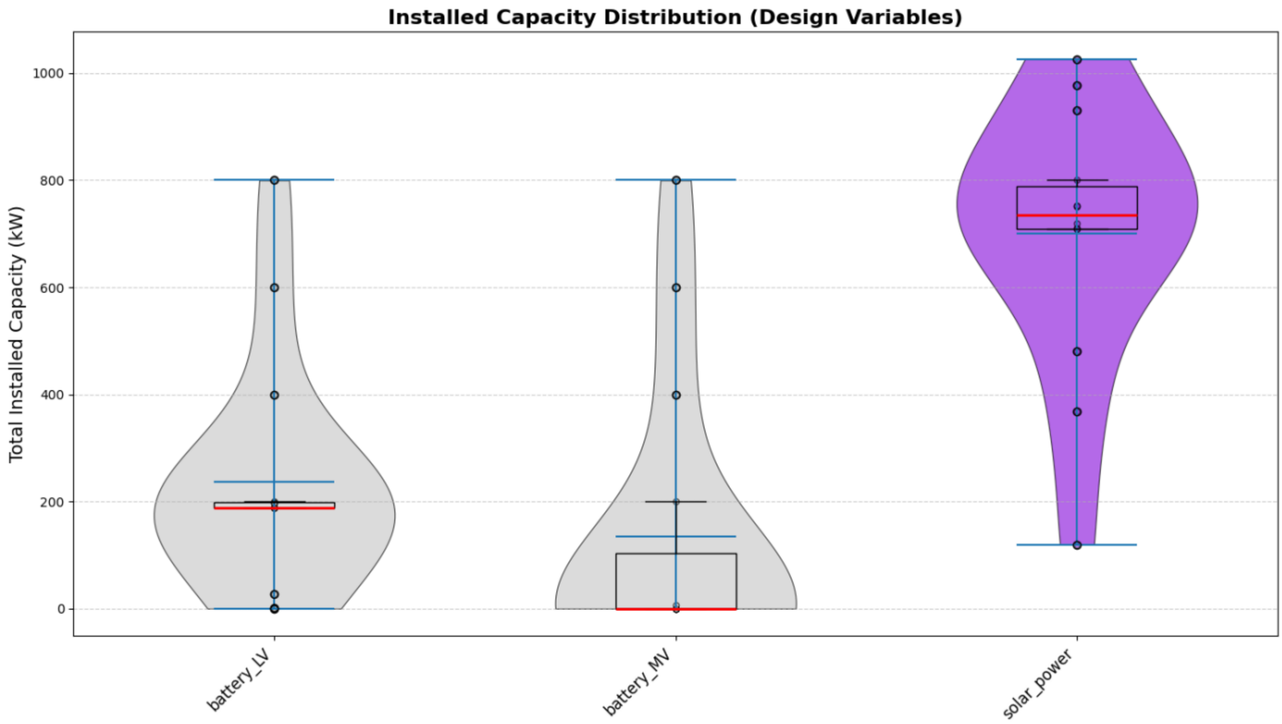

Figure 37: Installed capacity sensitivity obtained through the structural sensitivity analysis.

Figure 38 illustrates the sensitivity of operational variables derived from the structural sensitivity analysis, highlighting how variations in system configuration impact performance.

Curtailment shows a broad and dispersed distribution, reflecting variability across scenarios. High levels of curtailment occur in configurations with excessive solar PV capacity but insufficient storage or trading opportunities, revealing inefficiencies in renewable energy utilization. This observation aligns with our earlier findings that curtailment is primarily driven by system constraints, such as limited transformer capacity or battery storage. The sensitivity analysis confirms that curtailment is a key operational inefficiency, consistent with conclusions from Section 5.4.

Sell grid power has a narrow distribution, with consistently low values across scenarios. This is in line with our earlier observation that grid export opportunities are restricted by transformer capacity, limiting the ability to sell excess energy. The concentration of values further supports the robustness of the model's trading behaviour, reinforcing the conclusion that transformer capacity is a binding constraint, and that excessive PV does not increase the ability to export to the grid.

Supply grid power demonstrates big variability, with reliance on grid imports varying depending on renewable energy capacity and storage availability. Scenarios with high solar PV and sufficient storage exhibit lower grid imports, while scenarios with minimal renewables or insufficient storage show higher dependence on the grid. This behaviour validates the model's reliance on grid supply as a critical balancing mechanism. Additionally, we observe no scenarios with zero grid supply, indicating that we do not find any self-sufficient scenarios. This confirms the robustness of findings related to the essential role of grid imports in meeting demand in section 5.4.

Unmet demand is negligible across all scenarios, with values clustering near zero. This confirms the validity of the model's ability to satisfy demand under all structural variations, consistent with earlier results.

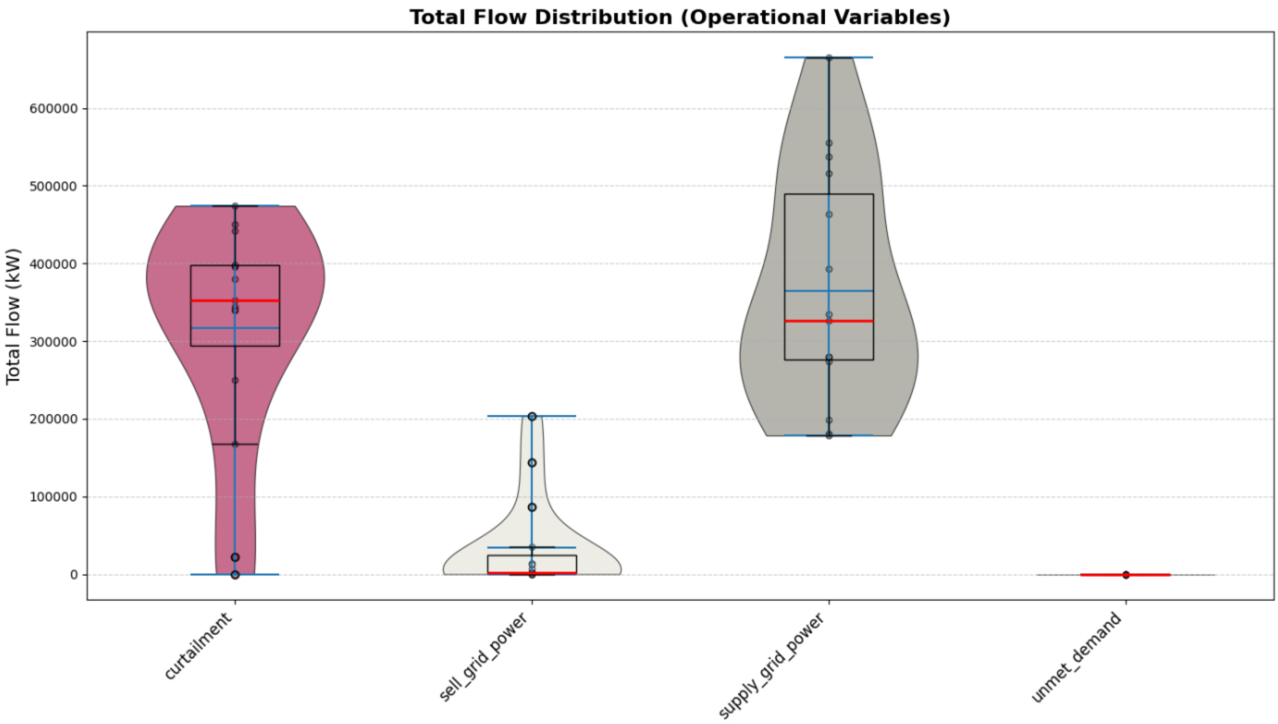

Figure 38: Annual flow sensitivity identified through the structural sensitivity analysis.

The structural sensitivity analysis confirms the robustness of the model's findings while providing nuanced insights into the roles of key assets in the system. Solar Power capacity emerges as a crucial driver for CO_2 reduction, with lower installations resulting in greater reliance on grid imports and significantly higher emissions. LV battery storage is essential in optimizing renewable energy use, reducing CO_2 emissions, and enabling time-shifting of energy generation and consumption. However, its impact diminishes beyond 200 kW, where additional capacity delivers limited CO_2 reductions and sharply increases costs due to high investment requirements.

MV battery storage demonstrates viability up to 200 kW, where it reduces monetary costs. However, beyond this threshold, its operational benefits decline due to limited trading opportunities with the MV grid, leading to increased costs and diminished contributions to system performance. Curtailment remains an inefficiency in scenarios with high Solar Power capacity and insufficient storage or trading opportunities. Here it becomes clear that transformer constraints restrict grid export potential. Across all scenarios, grid imports remain necessary to meet demand, with no self-sufficient configurations observed.

5.6. Parametrical Sensitivity Analysis

In Figure 39 we illustrate how the parameter sensitivity scenarios differ from the identified Pareto front. First, it is important to note that limiting the transformer to 0, gives an infeasible result, as there are not self-sufficient scenarios available within our model constrains. We therefore removed it from the visualisation.

We observe that the extreme scenarios align with expectations, as the Dirichlet distribution effectively filtered out less relevant configurations by focusing on a range of values skewed toward the base weight. This approach was chosen to highlight the most meaningful results and refine the Pareto front. Upon examining the extreme scenarios, we see that they cluster at the boundaries where the model becomes less sensitive to trade-offs with other objectives. Importantly, these scenarios follow the same parabolic trend observed in earlier analyses, confirming the consistency of the model's behaviour. For example, the synergy between sustainable and secure objectives remains evident, as extreme sustainable scenarios closely resemble extreme secure scenarios, with minimal differentiation in their Pareto front positioning. This validates our assumptions in Section 5.1 and underscores the robustness of the observed trends.

Lower LV battery prices reduce both monetary costs and CO_2 emissions at the same time. This result substantiates the role batteries have in the system. By enabling a time shift in both production as consumption patterns, the system is less reliant on the MV grid and can even sell to it due to more demand at different times than solar availability. Furthermore, we can conclude that the costs associated with buying LV batteries is substantial. It is important to note that there is limited sensitivity when it comes to the MV battery price which is about half the price of LV batteries in the base model.

Lastly, we observe that the solar price is predominantly tied to CO_2 emissions. Apparently, solar panels can be cost neutral in monetary terms, until a certain capacity threshold. Lowering the costs of solar panels helps the business case to a point where more capacity can be installed. This lowers the amount of grid interactions needed to sustain demand and therefore lowers CO_2.

Low electrification demand reduces both CO_2 emissions and monetary costs, as the system faces lower demand. High electrification demand causes transformer overloading, resulting in substantially higher costs and CO_2 emissions due to insufficient system capacity to meet demand. If we rerun the model, we find that there are a substantial number of configurations that are not feasible. Therefore, future work should address asset upgrades, such as transformer capacity, to handle increased demand due to electrification.

Three key observations are made regarding price sensitivity. First, scenarios where the system can sell energy for €0.27/kWh generate revenue, resulting in negative costs. This outcome confirms that the model functions as intended, demonstrating correct selling functionality. However, this result is unrealistic, as no sell price above €0.13/kWh is observed in real-world scenarios. Second, fixing the price at €0.13/kWh, the average day-ahead price, yields results similar to the base scenario. Lastly, fixing prices at the retail rate (€0.27/kWh), which is nearly double the day-ahead price, predictably increases system costs due to higher purchase prices. This indicates that the observed cost increase is solely a result of price magnitude and does not require rerunning the analysis, as the impact is directly attributable to the fixed price increase.

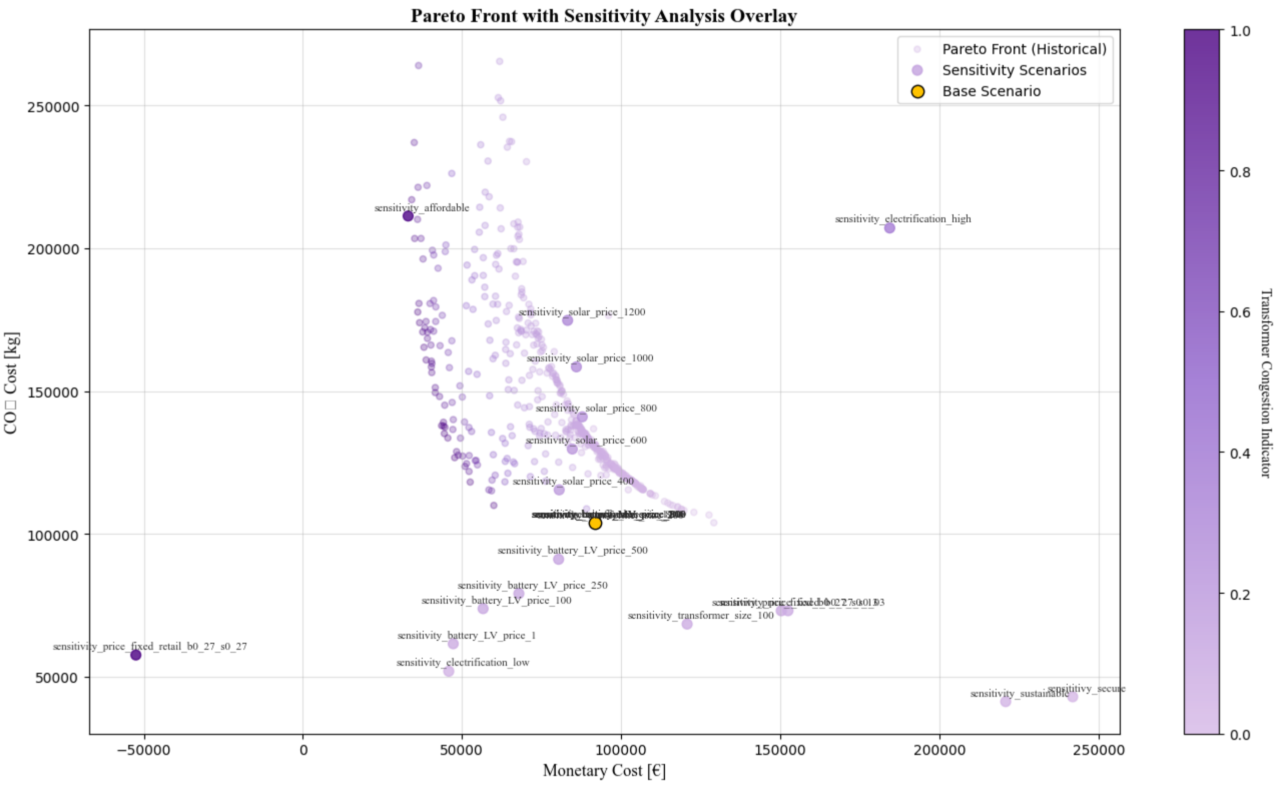

Figure 39: Parameter sensitivity runs compared to the identified Pareto front.

From Figure 40, it is observed that the distribution of LV battery capacity is broad, with most scenarios clustering around 200 kW. This indicates that LV batteries play a central role in balancing monetary cost reductions and CO_2 emissions. Beyond 200 kW, additional capacity yields diminishing returns in CO_2 reduction, while investment costs increase sharply. The variability in LV battery capacity highlights its sensitivity to system configuration and its effectiveness in addressing grid interaction and self-sufficiency.

The MV battery capacity shows a narrow distribution, consistently remaining at lower levels across all scenarios. This reflects its limited contribution to reducing costs or improving system performance. The results suggest that MV battery usage remains minimal across the model's configurations, aligning with the earlier observation that MV batteries are less impactful under the modelled conditions.

Solar Power capacity is predominantly installed 800 kW across all scenarios. This reflects the critical role of Solar Power in reducing CO_2 emissions by displacing grid electricity. The consistent installation of maximum Solar Power capacity aligns with the operational analysis, which identified Solar Power as a primary driver of CO_2 reduction. The lack of variability suggests that the system prioritizes renewable energy generation to its fullest extent whenever possible.

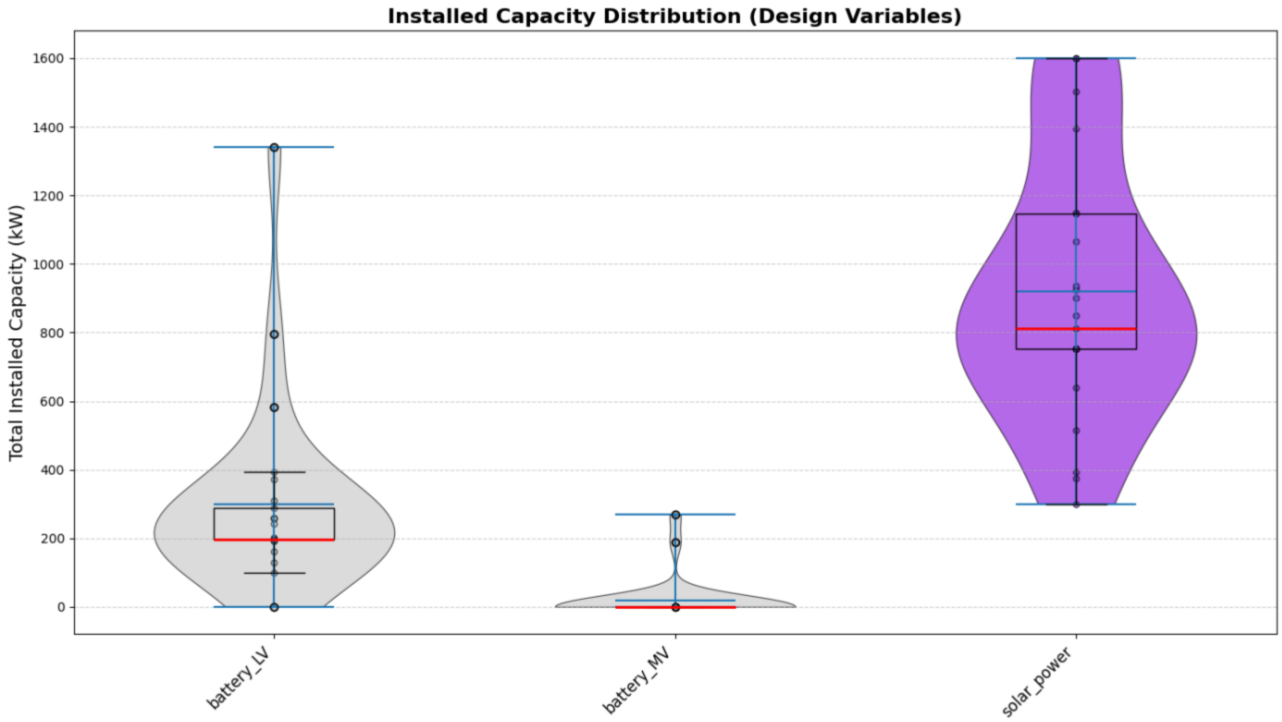

Figure 40: Installed capacity sensitivity identified through the parameter senstivity analysis.

In Figure 41, Curtailment exhibits the widest distribution among the operational variables, with values ranging significantly across scenarios. High curtailment levels are linked to configurations where Solar Power is installed at maximum capacity, but the system lacks sufficient storage or trading opportunities to utilize excess energy effectively. This reflects inefficiencies in renewable energy utilization caused by system constraints, such as limited grid export or storage capacity. The upper tail of the distribution highlights extreme cases with significant energy waste.

The distribution of sell grid power is narrow and concentrated, indicating limited variability in the ability to sell excess energy to the grid across scenarios. The median and interquartile range suggest that the system consistently exports a low amount of energy. This is primarily constrained by transformer capacities, which cap the total energy that can be exported.

Supply grid power shows a relatively wider distribution compared to sell grid power, reflecting more variability in the system's reliance on grid electricity. Scenarios with high Solar Power and sufficient battery storage exhibit lower reliance on grid imports, while configurations with limited renewable energy generation or storage show higher dependency. However, we identify no scenarios without grid imports. The results indicate that grid supply plays a critical role in balancing demand, particularly in scenarios where renewable generation is insufficient.

In this analysis, again, unmet demand is zero across all filtered scenarios. This confirms the validity of the model's ability to satisfy demand under all parameter variations.

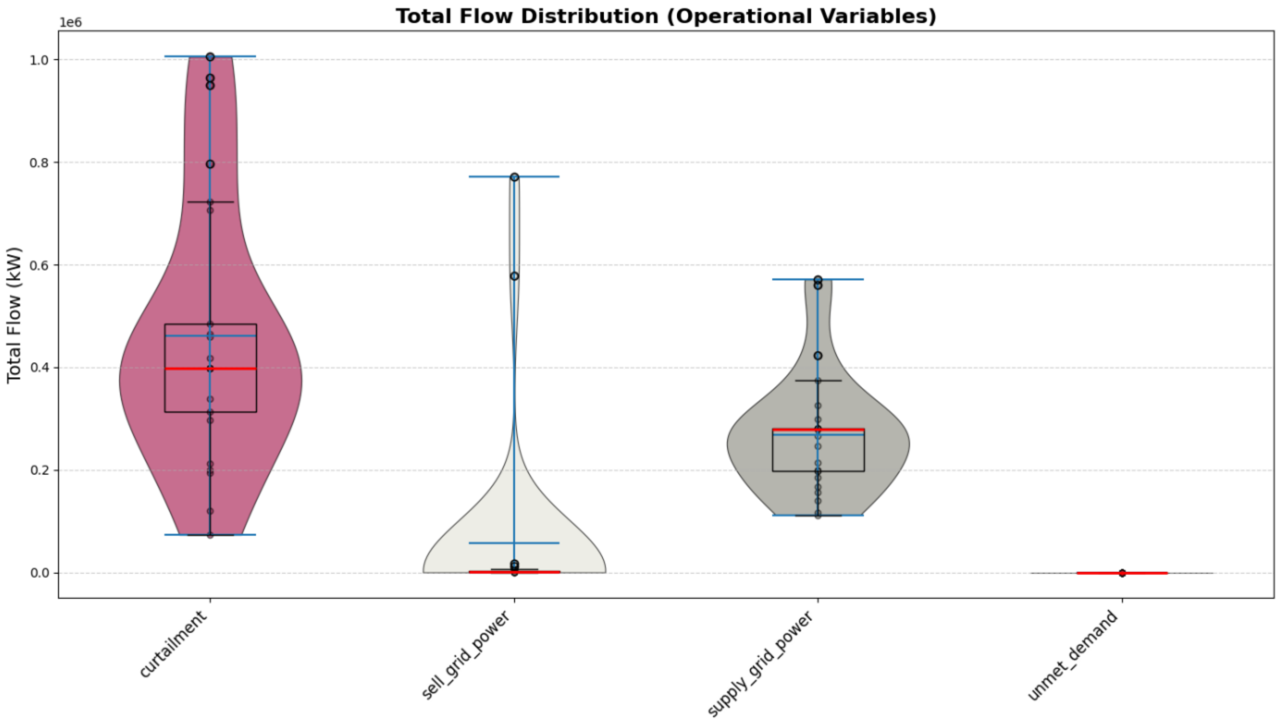

Figure 41: Annual flow sensitivity identified through the parameter sensitivity analysis.

6. Discussion

This chapter gives context to the results. First, we describe how the research findings relate to the literature identified in section 2.2. Thereafter, we describe the broader implications of the research findings by looking beyond the scope of this research. Lastly, the known limitations to this research are given to provide context to the conclusions of this research, following in section 7. By discussing these points, this chapter clarifies the contributions and boundaries of the research while highlighting how its insights fit into the bigger picture of the energy transition.

6.1. Research Findings

The Pareto front analysis confirms the inherent trade-offs between affordability, sustainability, and grid security, a conclusion widely recognized in the literature (Backe et al., 2022; Ponnaganti et al., 2023). The clustering of solutions along the Pareto front aligns with prior studies emphasizing that energy planning decisions do not yield a single optimal solution but instead present a spectrum of trade-offs (Secchi et al., 2021). Our results show that affordability is inversely related to sustainability and security, while sustainability and security objectives tend to align in extreme scenarios in both design and operation. Below, we discuss how these trade-offs manifest across the three pillars of the energy trilemma and how they compare to the literature.

Affordability

Affordability-focused REC configurations in this study prioritize cost minimization through high reliance on grid interactions and price arbitrage. This aligns with previous research that identifies financial viability in RECs as being strongly linked to demand-side management and battery storage strategies (Awad & Gül, 2018; Chakraborty et al., 2020). However, unlike studies that primarily frame affordability in terms of cost savings, our findings highlight that affordability-driven strategies can create grid congestion risks, reinforcing the concerns raised by Canizes et al. (2023) regarding the necessity of balancing cost efficiency with grid security.

Moreover, the observed sensitivity of affordability to electricity pricing structures supports findings by Lampropoulos et al. (2018) that market price dynamics significantly shape the financial attractiveness of RECs. It is important to note that the identified REC business models dependent on market trading remain viable under current conditions but may become less profitable over time as more RECs participate in electricity markets, reducing price volatility and arbitrage opportunities (Hennig et al., 2023). This is supported by findings by Backe et al. (2022), which indicate that widespread REC adoption alters market price dynamics, ultimately diminishing arbitrage potential.

Sustainability

The sustainability-focused scenarios in this study highlight the challenge of renewable energy curtailment, particularly in cases with high PV penetration, where the ‘Sustainable and Secure’ cluster experiences a curtailment ratio of 56%. This is consistent with Weckesser et al. (2021) and Crowley et al. (2023), who demonstrate that increasing renewable energy deployment without adequate flexibility mechanisms results in inefficient energy utilization. Our findings indicate that curtailment persists even with optimised battery capacity. This supports the argument by Backe et al. (2022) that renewable energy integration must be coupled with enhanced demand side flexibility mechanisms (which were excluded from this thesis due to the complexity of such mechanisms) to avoid inefficiencies.

Grid feed-in restrictions further increase curtailment, reinforcing Bonfert (2024), who argues that restrictive grid tariffs undermine the financial viability of high-renewable RECs. Without clear incentives for exporting excess generation, renewables are underutilized, a finding consistent with Secchi et al. (2021), who show that self-sufficiency alone does not guarantee economic feasibility. These results suggest that effective policy design is needed to facilitate renewable energy integration.

Security

The study introduces the Transformer Congestion Indicator (TCI) as a proxy for assessing grid security, aligning with prior research on congestion management in distributed energy systems (Estanqueiro et al., 2023; Hennig et al., 2023). Our results indicate that prioritizing grid security often leads to higher costs, confirming findings by Lampropoulos et al. (2019) that while flexibility solutions can stabilize the grid, they may not always be economically optimal.

Our results also align with research on real-time grid pricing and congestion management (Hennig et al., 2024). The Transformer Congestion Factor (TCF), used in our study to penalize grid interactions during peak periods, serves as a simplified congestion proxy. However, as suggested by Hennig et al. (2024), incorporating real-time congestion pricing could refine this approach, making REC-grid interactions less prone to induce congestion.

It is important to note that studies such as Bonfert (2024) identify risks associated with uncoordinated REC adoption, which could lead to new congestion challenges, particularly at the mid-voltage level. We corroborate such concerns as we observe new consumption and feed-in peaks introduced by the RECs. If RECs would exemplify this behaviour on a large scale without coordination, it could lead to new congestion issues.

Sensitivity Analysis

The structural and parametric sensitivity analyses highlight diminishing returns on battery and solar PV investments beyond a certain threshold. Similar trends are reported by Secchi et al. (2021), who found that battery scaling has non-linear economic benefits. Our study extends these findings by quantifying the diminishing impact of increasing LV and MV battery storage, demonstrating that beyond 200 kW per 200 prosumers, additional investments provide minimal CO_2 reductions while substantially increasing costs. Similar conclusions can be drawn for PV, which shows diminishing returns after 750 kW per 200 prosumers.

Additionally, our results confirm findings from Bonfert (2024) that full REC self-sufficiency is rarely achievable under real market conditions, as grid imports remain necessary to balance demand and generation, especially during winter. This supports arguments made in Backe et al. (2024), who show that REC models designed around full self-sufficiency often leads to inefficiencies.

Finally, battery placement plays a critical role in congestion management. Our findings support (Plaum et al., 2022) and Weckesser et al. (2021), showing that LV batteries effectively shift local demand to reduce congestion, whereas MV batteries primarily facilitate grid trading rather than congestion relief. This reinforces recommendations by Ponnaganti et al. (2023) for an integrated approach to battery deployment that accounts for both local demand flexibility and broader grid interactions.

6.2. Implications of the Research

In this section, we describe the implications of the results of this research. To do so, we go beyond the scientific scope and give our knowledge of the field which was corroborated with Accenture and the TU Delft Supervisors. This is done to give context to the results and show the societal impact of RECs.

First, we note that the transition towards a decentralised energy system presents both technical opportunities and institutional challenges. Renewable Energy Communities (RECs) offer a structured approach to local energy sharing, creating an alternative to traditional top-down grid management. By enabling communities to collectively own and manage distributed energy resources (DERs), RECs establish a balance between decentralisation and coordination, fostering greater efficiency in both energy distribution and market integration. However, their widespread adoption raises critical questions regarding infrastructure pricing, market roles, and long-term economic feasibility. These topics are discussed in this section.

Efficiency Gains and Grid Integration Challenges

Energy is inherently local, and its most efficient use occurs close to the point of generation. A key challenge introduced by the rise of distributed energy resources (DERs) is that centrally organised actors, such as DSOs, will struggle to manage the local grid issues that arise from decentralised generation and consumption patterns. As observed in this thesis, prosumption behaviour becomes less predictable, making it more difficult for DSOs to anticipate grid congestion and balance supply and demand. The lack of real-time, granular data on local energy flows further complicates this process, as traditional energy market structures rely on retailers to forecast and manage consumption trends that are now increasingly volatile. Without new coordination mechanisms, DSOs may face growing difficulties in ensuring grid stability and preventing inefficiencies at the distribution level.

RECs introduce a more centralised framework, allowing communities to optimise self-consumption and reduce reliance on external grid imports while maintaining a structured level of coordination. One of the primary advantages of RECs is their ability to aggregate demand and generation, effectively functioning as single market entities when interacting with the mid-voltage grid. This enables them to participate in flexibility markets, shifting demand to align with renewable energy availability and alleviating stress on the network. Here we observe that we can decentralise energy assets whilst centralising governance by introducing an actor that oversees a physical neighbourhood, instead of the dispersed retail contracts we currently have.

However, while individual REC actions may contribute to improved grid balancing, coordinated behaviour at scale may have unintended consequences. If many RECs respond to similar market signals, such as charging storage at low prices and exporting surplus energy at peak demand, this could lead to congestion at the mid-voltage level rather than mitigating grid stress. Therefore, clear coordination is needed with the balancing responsible party such as the DSO.

Infrastructure Cost and Pricing Mechanisms

The introduction of RECs brings with it the potential for new pricing models for grid infrastructure. Traditionally, grid connection fees are applied as static costs for households, meaning all users pay a fixed rate regardless of when they use the grid infrastructure. However, congestion is a time-dependent issue rather than a fixed capacity constraint as we have observed throughout this thesis. Therefore, a more dynamic pricing approach would distribute grid costs in a manner that reflects actual usage, charging participants based on their contribution to congestion rather than a uniform fee.

In conventional energy systems, implementing such a pricing structure is difficult, as it would require retailers to track individual consumer usage patterns, coordinate with distribution system operators (DSOs), and dynamically adjust payments. Within a REC, however, a single entity oversees all transactions, making real-time pricing adjustments significantly more feasible. This could lead to more efficient grid use, as REC members would have a direct incentive to shift consumption away from peak transformer strain periods in order to reduce costs.

Changing Market Roles and Institutional Responsibilities

The aggregation of local generation and consumption within an REC fundamentally alters traditional market roles. Unlike conventional energy consumers, REC participants are not reliant on retail suppliers for electricity purchasing, instead prioritising self-consumption and internal energy trading. While this eliminates inefficiencies associated with multiple intermediaries, it raises broader concerns regarding pricing mechanisms, cost equity, and long-term market stability.

As RECs displace retail suppliers, financial risks shift within the market. Retailers operate across broad geographic areas, making them more resilient to localised disruptions. In contrast, an REC functions within a single community, meaning its financial stability is tied directly to local market conditions. If an REC is unable to manage its finances effectively, experiences unexpected price fluctuations, or encounters operational inefficiencies, its participants may be exposed to unstable energy supply. This introduces concerns about consumer protection, particularly if the aggregator responsible for managing the community lacks the financial capacity to absorb short-term market shocks.

Beyond the retail market, the increasing role of RECs may also require DSOs to take on additional responsibilities. As RECs become more active in market operations, potentially trading flexibility services and coordinating demand response, DSOs may be required to play a more direct role in managing local grid stability. While this shift could improve grid predictability and simplify system coordination, it also raises regulatory challenges. If DSOs are to assume greater responsibility in energy market operations, clear mechanisms will be required to ensure consumer rights are protected.

Long-Term Viability and Scalability of RECs

The long-term economic feasibility of RECs depends on the evolution of market conditions. Early adopters benefit from favourable grid interactions and cost reductions, but as RECs become more widespread, the market value for locally traded energy may diminish. If too many communities engage in similar optimisation strategies, their collective impact on balancing services may weaken, reducing potential revenue streams. This raises the question of whether RECs will remain financially attractive once their market presence expands, or whether their viability will become increasingly dependent on policy incentives and structural support.

Additionally, widespread REC adoption could introduce new grid challenges, as previously described. If the RECs are not coordinated effectively, their behaviour could increase MV level congestion. This makes it difficult to predict whether their benefits will scale effectively over time.

However, given current constraints on grid expansion, RECs could offer a solution for integrating new energy connections while improving the efficiency of existing infrastructure. This is particularly relevant for newly developed neighbourhoods, where electrification is driving increased electricity demand. As new residential developments increasingly exclude gas connections and rely exclusively on electricity, integrating RECs into urban planning could optimise grid use, mitigate the need for costly reinforcements, and shorten the time to connect new neighbourhoods.

Conclusion to the Research Implications

RECs offer an efficient alternative to traditional energy market structures, but their integration into the broader electricity system requires careful consideration. Their ability to function effectively will depend on evolving market conditions, emerging technologies, and regulatory frameworks.

The shift from retailers to aggregators, the introduction of dynamic grid pricing, and the potential for local balancing services present opportunities to improve grid efficiency and system flexibility. However, these same factors introduce new risks, particularly in terms of financial resilience, consumer protection, and overall market predictability.

Ensuring that RECs remain a viable and scalable energy solution will require further research into pricing models for internal energy trading, financial risk mitigation strategies for aggregators, and the role of DSOs in managing REC interactions. As market structures continue to evolve, it will be necessary to develop scalable institutional frameworks that support local energy trading while maintaining stability across the broader electricity system.

The long-term success of RECs will ultimately depend on their ability to balance decentralisation with system-wide reliability, ensuring that they contribute to a more resilient, flexible, and consumer-friendly energy market.

6.3. Limitations

While this thesis has aimed to provide a comprehensive and generalizable framework for the design and operation of Renewable Energy Communities (RECs), several limitations remain. These are primarily related to challenges in the literature review, the objectives defined in the MO LP optimisation, and broader dynamics beyond the model’s scope. These limitations are outlined below to provide transparency and guidance for future research.

Challenges in the Literature Review

The fragmented and inconsistent terminology within the emerging field of energy systems optimization posed significant challenges during the literature review. Studies addressing similar optimization problems often adopt varying terminologies, methodologies, and assumptions, making it difficult to systematically identify, compare, and synthesize findings. This fragmentation was particularly evident in interdisciplinary topics such as policy frameworks, grid flexibility, and community-level energy strategies.

Although every effort was made to review a wide range of sources, it is possible that some relevant studies were overlooked, or certain insights were underrepresented. Furthermore, the simplicity of the Transformer Congestion Factor (TCF) developed in this thesis suggests it may not be entirely novel. While the literature did not the same approach, the fragmented nature of the field leaves room for uncertainty regarding the originality of this contribution.

Static Factor for the Sustainability Objective

The REC model employs a static CO_2 emission factor for grid imports, which does not account for the dynamic nature of carbon intensity in the national grid. This simplification creates conflicts with other indicators used in the model, such as price and the Transformer Congestion Indicator (TCI). For instance, when grid prices are high, this typically reflects high demand, which likely involves the operation of non-renewable energy sources and thus higher CO_2 intensity. Conversely, during periods of abundant renewable energy (low CO_2 intensity), grid prices are often lower due to high renewable feed-in, but the model discourages imports during these low-price periods, contradicting the sustainability objective.

Furthermore, the TCF penalizes feed-in during high-demand periods to avoid transformer congestion, yet such feed-in could reduce overall grid emissions by displacing non-renewable generation. The absence of CO_2-related incentives for feed-in exacerbates this contradiction, as the model neither rewards feed-in during high-carbon periods nor aligns with the broader goal of supporting national grid decarbonization. Addressing these conflicts would require dynamic CO_2 factors that reflect real-time grid conditions and introducing feed-in incentives to prioritize sustainability dynamically in alignment with price and TCF signals to avoid wasteful RES curtailment.

Formulation of the Security Objective

While the Transformer Congestion Factor (TCF) introduced in this study provides a novel approach to modelling grid congestion in the absence of detailed congestion time series data, several limitations remain in its current formulation. The primary challenge lies in the absence of a normalisation constant in the mathematical formulation that defines the average cost of transformer usage, leading to an inherent bias in how congestion penalties are applied.

One of the key assumptions in this model is that whenever the transformer is used, a cost is incurred, even when the grid is not congested. In reality, congestion pricing should be proportional to the level of transformer overloading, starting from a near-zero cost under normal operating conditions. However, due to the absence of a normalisation constant, the model imperfectly balances import and export congestion costs, causing the TCF values to fluctuate around 0.5 over time. This does not fully align with real-world grid conditions, where grid security is not always compromised, and complete self-sufficiency is not always necessary. Additionally, feed-in and consumption congestion do not necessarily have the same impact on grid operations, and future refinements should allow for differentiated congestion costs.

The impact of this assumption is that completely avoiding transformer usage is highly prioritised in the optimisation model, as any use incurs an immediate cost. This leads to an overemphasis on self-sufficiency, which, while beneficial, may not represent the most optimal or realistic energy-sharing strategy. A dynamic pricing scheme should instead be introduced, where congestion costs are only applied when the transformer is overloaded, ensuring that REC behaviour better reflects real grid constraints. However, setting the TCF to zero during non-congested periods would introduce negative values in the objective function, inadvertently incentivising transformer usage when prices are low, which is equally unrealistic. Future refinements should focus on scaling congestion costs proportionally to transformer stress levels, preventing extreme incentives for self-sufficiency while ensuring that grid interactions remain efficient and aligned with real-world congestion dynamics.

Despite these limitations, the multi-objective (MO) optimisation framework allows for some flexibility in balancing these imperfections, as the weightings in the objective function can be adjusted to relax or reinforce the impact of the TCF. Furthermore, the primary purpose of the TCF was not to provide a perfect congestion pricing mechanism, but rather to track transformer usage at problematic times, which proved far more relevant to congestion mitigation than simply measuring total transformer usage.

Behavioural Feedback on Market Dynamics

The model assumes static day-ahead prices as an external input, excluding feedback loops between REC operations and electricity market dynamics. However, as RECs, battery storage, and coordinated energy trading become more widespread, they could alter market conditions, influencing price volatility and demand-supply balance over time.

For instance, if many RECs charge batteries during low-price periods and export surplus energy when prices peak, these predictable behaviours could create ‘negative’ feedback loops on the market dispatch, stabilising market prices. Since the model focuses on a single REC rather than the cumulative impact of multiple RECs, it does not capture these long-term shifts in price signals or their effect on operational decisions. As market dynamics evolve in response to widespread REC adoption, the resulting changes in price patterns could, in turn, alter REC behaviour, leading to different optimisation strategies than those predicted by this study.

Beyond market feedback loops, this study does not assess whether multiple RECs operating simultaneously could introduce new congestion patterns at the MV level. While individual RECs are designed to reduce transformer congestion and enhance self-consumption, their collective behaviour could create new operational challenges for grid balancing, particularly if many RECs respond to the same market signals without coordination.

This concern is reinforced by new peak loads and export spikes observed in certain scenarios, suggesting that while a single REC optimises its grid interactions, uncoordinated REC adoption on a larger scale could introduce unintended congestion issues at the MV level. Since the study focuses solely on transformer usage, it does not account for how REC electricity flows through the broader distribution network, where congestion could arise beyond transformer bottlenecks. If multiple RECs synchronize their grid interactions, DSOs may struggle to maintain local balance, particularly in regions with limited flexibility options.

Additionally, this study does not explicitly model other assets at the MV level, such as MV-scale battery storage, wind farms, or other distributed generation sources. These assets also respond to price signals, and their participation in flexibility markets could further alter local market conditions, price volatility, and congestion patterns. Since these factors are highly location-specific, this study takes a generalized approach, focusing on RECs as independent entities rather than incorporating specific regional energy system characteristics.

7. Conclusions

In this section, we first give answers to each sub-question. These findings are combined, leading to a conclusion of this thesis by answering the overarching research question. Thereafter, we give future research directions to expand on this work.

7.1. Answers to the Research Questions

Sub-Question 1

The first sub-question asked:

"What are the components and mechanisms that are to be considered when designing a generalizable Renewable Energy Community in the Dutch urban context?"

The model incorporates solar photovoltaics (PV) as the primary decentralized energy source. To manage fluctuations in generation and consumption, battery storage is included at two levels: LV storage at individual households and MV storage at the transformer.

The LV grid is modelled as a radial configuration with 200 connections divided into five branches. In these branches, energy demand is modelled using E1 and E2 archetypes to represent residential and small commercial consumers. These profiles capture the diversity of urban energy usage. The model assumes fixed demand patterns, excluding behavioural adjustments like demand response due to its complexity.

A defining mechanism of the REC model is its centralized market structure. Within the low-voltage (LV) system, energy sharing is conceptualized as costless flows, allowing surplus generation or excess demand at individual prosumer nodes to be balanced internally without explicit transactions. This approach eliminates the need for household-level retail contracts and optimises the REC for collective outcomes, minimizing total system costs rather than individual expenses. In practice, mechanisms like energy accounting or peer-to-peer pricing would be required to ensure fairness, but these are excluded here.

The grid interactions are centralized at the transformer, which serves as the single point of connection between the REC and the mid-voltage (MV) grid. The transformer node supports imports and exports based on day-ahead market pricing, enabling the REC to respond dynamically to external price signals while maintaining operational simplicity. By consolidating imports and exports at this single node, the REC operates as a unified market participant, aligning with EU directives for energy communities.

This design allows for the operational realities of urban grids, where transformers act as natural bottlenecks, causing congestion in urban areas. By focusing on transformer capacity rather than cable routes, the model captures the primary drivers of congestion in urban electricity systems. However, this simplification abstracts away some of the detailed network characteristics, such as voltage regulation or specific cable constraints, which may vary between locations.

While the inclusion of additional flexibility solutions, such as electric vehicles (EVs), heat pumps, and thermal storage, could provide further insights, their absence is not expected to fundamentally alter the core dynamics of the system. The model captures the key interactions between decentralised generation, storage, and grid congestion, which remain central regardless of the specific flexibility technologies used. Moreover, these emerging technologies are not yet available in all locations, and their adoption varies widely across regions. In contrast, solar PV and battery storage are already deployed at scale and are relevant to energy communities today.

Given the urgency of the energy transition, this study prioritises components that can be implemented immediately in any location, ensuring that the insights provided are actionable for policymakers in the present context.

Sub-Question 2

The second sub-question asked:

"How can we mathematically optimise the design and operation of a Renewable Energy Community for dimensions of the Energy Trilemma (affordability, sustainability, and grid security)?"

The Renewable Energy Community (REC) model employs a multi-objective linear programming (MO LP) framework to address the energy trilemma dimensions of affordability, sustainability, and grid security. Each dimension is represented as an objective function, with trade-offs analysed through a weighted sum. By assigning weights to each objective, the model explores how prioritising one dimension affects the others, generating a Pareto front that reveals trade-offs and synergies between the energy trilemma dimensions. This approach enables policymakers and stakeholders to evaluate the implications of different priorities and identify balanced configurations.

Affordability is captured through operational and capital costs, where operational expenditures are tied to hourly day-ahead market prices. Sustainability is measured via CO_2 emissions from grid imports, which is a static CO_2 equivalent. Grid security, conceptualized as transformer congestion, is included as a dynamic cost indicator. A significant challenge in the modelling process was the conceptualization of grid security. Urban energy systems often experience congestion at transformers, but obtaining location-specific congestion data is impractical for a generalisable model.

To address this, we introduced the Transformer Congestion Factor (TCF), a conceptual proxy based on day-ahead market prices. High market prices indicate periods of high demand and potential transformer strain, while low prices suggest low demand or high renewable feed-in, where excessive exports could lead to congestion. The TCF operates bidirectionally, penalizing transformer usage during high-demand periods and discouraging feed-in during low-demand periods. This approach provides a dynamic indicator of congestion without relying on unavailable data. The Transformer Congestion Indicator (TCI) aggregates these penalties over time, offering a dimensionless annual cost metric that reflects grid security.

While the TCF provides a flexible and generalisable representation of transformer congestion, it introduces certain limitations. By relying on market prices as a proxy, the model abstracts away localized grid characteristics such as voltage regulation or specific cable constraints. Additionally, the absence of real-time grid behaviour means the TCF cannot fully replicate congestion dynamics in specific locations. Despite these limitations, the TCF allows the model to capture broad trends in transformer usage, enabling an exploration of grid security that is adaptable across urban contexts.

The degrees of freedom in the model encompass both design and operational decisions, enabling it to optimise REC performance comprehensively. On the design side, the model determines the capacity of solar PV and battery energy storage systems (BESS) and their allocation between low-voltage (LV) and mid-voltage (MV) levels. Operationally, it optimises the hourly charging and discharging of BESS, energy imports and exports, and curtailment to balance generation and demand. These degrees of freedom allow the model to explore various configurations and operational strategies, revealing the trade-offs required to balance the energy trilemma dimensions.

The formalized REC model enables the dynamic exploration of trade-offs between affordability, sustainability, and grid security. The use of MO LP and the conceptualization of transformer congestion through the TCF provide a robust framework for analysing REC configurations in urban settings. By adjusting weights, the model highlights how different priorities impact the design and operations of a REC, and therefore its annual performance on the dimensions of the Energy Trilemma. This offers a tool to gain insights into the trade-offs required to achieve a balanced and efficient energy community.

Sub-Question 3

The third sub-question asked:

"What are the trade-offs between the most promising design and operation options for the generalized Renewable Energy Community?"

The optimization model highlights key trade-offs and systemic inefficiencies in the design and operation of Renewable Energy Communities (RECs), emphasizing the complexity of balancing affordability, sustainability, and grid security. Each scenario reflects different priorities, illustrating the inherent tensions between these objectives.

Interestingly, sustainability and grid-security-focused scenarios show overlapping design principles. Both prioritize self-sufficiency by reducing grid exports and increasing reliance on local energy resources. However, achieving these objectives requires significant investments in renewable energy and storage infrastructure, resulting in lower affordability. This behaviour highlights the tension between the energy trilemma dimensions, where improvements in one area often led to sacrifices in another.

In terms of design, solar PV capacity effectively reduces grid reliance and CO_2 emissions but often results in significant curtailment. This inefficiency occurs when excess energy cannot be stored or exported due to transformer feed-in constraints. Notably, this is a result of the TCI, as solar potential tends to peak during hours when feeding into the grid is most problematic. Although solar PV enhances sustainability, the inability to fully utilize generated energy reflects systemic inefficiencies in grid-constrained systems. Still, as of the day of modelling, we would recommend a system of 200 prosumers to install 750kW of solar.

Batteries play a critical role in smoothing energy flows and reducing grid dependence. Low-voltage (LV) batteries are particularly effective in managing grid interactions and lowering emissions, but their cost-effectiveness diminishes beyond a capacity of approximately 200 kW for a 200-prosumer community. Medium-voltage (MV) batteries, designed for grid trading, show minimal benefits beyond 200 kW. These findings suggest that while batteries are indispensable for REC functionality, their economic viability is closely tied to the rest of the system design and operation.

Operational dynamics reveal further complexities and trade-offs. Across scenarios, batteries are used to optimise energy flows by charging during low-price periods, typically at night, and discharging during peak-price hours. This operational strategy effectively balances daily supply-demand mismatches but varies in its outcomes depending on scenario priorities. In affordability-focused scenarios, frequent trading and price arbitrage happen to reduce costs but increase transformer congestion and CO_2 emissions. Conversely, sustainability and grid-security scenarios prioritize self-consumption, avoiding congestion but leading to higher curtailment during peak solar production. These patterns underscore the difficulty of fully integrating renewable resources without creating inefficiencies.

Moreover, the model assumes no incentives for exporting sustainable energy beyond price, which limits the exploration of strategies that could further integrate renewable sources into the grid. This result raises important questions about how to limit curtailment while maximizing installed solar PV capacity per household. The model suggests that grid upgrades or alternative mechanisms to accommodate increased solar feed-in are essential for improving system efficiency in term of curtailment.

Overall, the results emphasize recurring trade-offs and synergies in REC design and operation. While sustainability and grid security objectives often align, achieving these goals typically requires sacrifices in affordability. Furthermore, persistent curtailment, reliance on grid imports, and temporal misalignment of environmental and economic priorities highlight systemic inefficiencies that are still to be addressed.

Research Question

The sub-questions are used to answer the main research question:

"How can Dutch urban Renewable Energy Communities be designed and operated to enhance energy affordability, sustainability, and security?"

The research demonstrates that there is no universally optimal design or operational strategy for Renewable Energy Communities (RECs). Instead, the effectiveness of any configuration depends heavily on the priorities and perspectives of the stakeholders involved.

Despite the diversity in optimization outcomes, several robust conclusions hold across all scenarios. Dutch urban Renewable Energy Communities (RECs) can be designed and operated to enhance energy affordability, sustainability, and security by installing around 750 kW of solar PV capacity per 200 prosumers and adopting 200 kW of MV and 200 kW of LV batteries for hourly balancing and optimizing grid interactions in response to market signals. Grid reliance is inevitable in all configurations, particularly during winter, highlighting the critical role of robust transformer infrastructure. Lastly, while PV consistently drives sustainability outcomes, its integration is constrained by curtailment, highlighting the need for targeted measures to align renewable generation with system constraints.

To address the challenges, a more dynamic and responsive approach is required. Dynamic congestion pricing should reflect real-time grid conditions, ensuring that feed-in occurs when system capacity allows while discouraging exports during congestion periods. Additionally, policies that incentivize storage deployment and demand-side flexibility can reduce curtailment by shifting consumption to periods of high solar generation.

Moreover, while transformer upgrades remain an option, they should not be seen as the default solution. The cost-effectiveness of grid expansion is highly dependent on localized congestion patterns, and a smarter allocation of existing grid capacity through flexible grid pricing and REC coordination could be a more efficient alternative. Ultimately, this study demonstrates that the combination of market-aligned operations, and storage deployment is critical to making RECs a viable and scalable solution for mitigating urban grid congestion while optimizing affordability and sustainability.

7.2. Future Work

This thesis provides a foundational understanding of how Renewable Energy Communities (RECs) can be designed and operated in urban Dutch contexts to optimise affordability, sustainability, and grid security. While the findings contribute to REC modelling and optimization, several areas require further research to enhance their applicability, scalability, and integration into the broader energy transition. Future studies should focus on refining REC models, assessing system-wide impacts, and exploring policy mechanisms that support large-scale deployment while ensuring grid stability and economic feasibility.

REC Integration and Feedback Loops with the MV Grid

The study primarily focuses on low-voltage (LV) grid operations, assuming that REC interactions with the mid-voltage (MV) grid are limited to imports and exports at day-ahead prices. However, as more RECs are integrated into the grid, feedback loops between RECs and MV grid conditions may significantly influence both REC operations and broader system stability.

Future research should investigate how large scale coordinated REC behaviour influences MV grid performance and how MV grid constraints, congestion, and market fluctuations shape REC decision-making. Large-scale system simulations could assess whether RECs serve as a congestion management solution or if uncoordinated behaviour introduces new operational challenges. The hypothesis is that actor coordination at the REC level could alleviate MV congestion by optimizing local flexibility. Conversely, widespread REC participation in market-based flexibility services could create new congestion patterns if not properly aligned with DSO strategies. Understanding these interactions is crucial for determining whether RECs provide a net benefit to grid stability or if additional coordination mechanisms are required.

Additionally, future research should integrate agent-based models or market simulations to assess how RECs collectively influence electricity price dynamics. If many RECs follow similar optimization strategies (i.e. charging batteries during low-price periods and exporting at peak times), market price signals could shift, altering REC profitability and operational incentives.

Understanding these interactions is crucial for ensuring that RECs remain economically viable as adoption grows. Additionally, research should explore how REC trading strategies could evolve in response to long-term market shifts, preventing unanticipated feedback loops that undermine their effectiveness.

Refining the Transformer Congestion Factor (TCF) and Market-Based Pricing

This thesis introduces the Transformer Congestion Factor (TCF) to capture grid security constraints in the absence of detailed congestion data. While the TCF provides a scalable method for including congestion costs in REC optimization, its current formulation assumes a static pricing mechanism that does not fully reflect real-world grid conditions.

Future research should focus on refining the TCF to incorporate dynamic pricing structures that better align with congestion severity and real-time grid constraints. A more nuanced congestion pricing scheme could prevent the model from overemphasizing self-sufficiency while ensuring that REC interactions remain efficient.

Multi-Objective Trade-Offs and Alternative Optimisation Approaches

The study applies Multi-Objective Linear Programming (MO LP) to balance affordability, sustainability, and grid security. However, it does not explore extreme scenarios where one objective is fully prioritized over the others. Investigating these trade-offs could reveal deeper insights into the independent and combined impacts of each objective on REC design and operation.

Future research could integrate Modelling to Generate Alternatives (MGA) methods to explore a wider range of near-optimal solutions, offering decision-makers more flexibility in selecting REC configurations based on policy priorities. Simultaneously, such a method would address the structural uncertainty from the modelling practices of this thesis.

Policy Development to Enable Scalable REC Adoption

As Renewable Energy Communities (RECs) gain traction, regulatory frameworks must evolve to accommodate their growing role in energy markets. Future research should explore policy mechanisms that balance the energy trilemma, ensuring affordability, sustainability, and grid security, while incentivizing REC behaviour that optimises both local energy use and system-wide efficiency.

A major policy challenge is aligning incentives for self-consumption with grid-wide flexibility needs. While maximizing local energy use can reduce congestion, RECs could also play a critical role in grid balancing and reducing CO2 eq if properly incentivized. Dynamic incentives should be introduced to encourage RECs to export surplus energy during periods of low congestion, reducing curtailment while discouraging exports when the grid is already strained. Similarly, pricing structures should reflect the true value of flexibility, rewarding RECs for contributing to grid stability rather than penalizing their interactions with the external network. Time-based grid connection pricing could further optimise grid efficiency by ensuring that REC imports and exports are cost-reflective to the infrastructure they use (i.e. transformers) and aligned with system needs.

Beyond pricing mechanisms, the evolving market structure must be addressed. The shift from traditional retailers to aggregators introduces new risks and responsibilities. Unlike large-scale retailers with diversified portfolios, aggregators typically operate within localized areas, making them more vulnerable to market fluctuations and financial instability. This increases the risk of REC participants facing unaffordable supply if an aggregator fails. Future research should examine how to mitigate these risks while ensuring aggregators can effectively manage REC flexibility services.

At the same time, Distribution System Operators (DSOs) are likely to assume greater responsibilities as the intermediary role of retailers diminishes. Without a retailer acting as a buffer, DSOs may need to coordinate directly with aggregators to manage flexibility and grid stability. Policymakers must clarify these responsibilities to prevent inefficiencies, ensure a well-integrated market structure, and protect consumers.

By addressing these challenges, future research can contribute to scalable REC frameworks that support the transition to a decentralized energy system while safeguarding energy affordability and equity, environmental sustainability, and security.

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All the results can be reproduced using the open-source GitHub directory associated with this thesis:

https://github.com/Tomdebruin/MO-LP-Energy-Community-optimisation

I acknowledge the use of AI tools. Specifically, ChatGPT and Co-pilot were used for assistance in refining grammar, and coding. All academic content, analysis, and conclusions are my own.

9. Appendix

A. Components of Renewable Energy Communities

Table 5: Considered components of a REC.

Component	Description	Included	Reason for Inclusion/Exclusion	Sources (Examples)
Battery Storage	Devices for storing excess electricity for later use.	Yes	Necessary for balancing supply and demand, increasing self-consumption, and enabling flexibility in RECs.	Secchi et al. (2021); Weckesser et al. (2021)
Curtailment	Mechanism to limit renewable output during overproduction or grid constraints.	Yes	Essential for managing overproduction and ensuring grid stability in renewable-based systems.	Chakraborty et al. (2020); Backe et al. (2022)
Demand Response	Adjusts energy consumption patterns in response to grid signals.	No	Requires complex behavioural and dynamic pricing models, outside the scope of this thesis.	Alabi et al. (2023); Crowley et al. (2023); Chakraborty et al. (2020)
District Heating	Centralized thermal energy distribution for buildings.	No	Excluded due to a focus on electricity systems, as thermal systems are beyond the scope of this study.	Alabi et al. (2023); Backe et al. (2022)
Electric Vehicles	Vehicles with batteries that can act as flexible energy storage through vehicle-to-grid (V2G) tech.	No	Integration into RECs is complex and not well-standardized, making it less feasible for this study.	Alabi et al. (2023); Hennig et al (2022).
Energy Trading	Peer-to-peer sharing of surplus energy between community members.	Yes	Relevant for modelling energy-sharing dynamics within RECs and aligns with EU policy directives.	DIRECTIVE (EU) 2019/944; Garavaso et al. (2021); Hennig et al. (2022).
Grid Interaction	The national grid infrastructure is used to either	Yes	Necessary for any system that is not self-sufficient.	Hennig et al. (2022); Weckesser et al. (2021).

	buy or sell electricity.			
Heat Pumps	Devices for heating and cooling buildings using renewable electricity.	No	Focus is on electricity systems; modelling thermal systems would add unnecessary complexity to this scope.	Alabi et al. (2023); Backe et al. (2022); Hennig et al. (2022).
Local Transmission	Infrastructure for distributing electricity within the community.	Yes	Fundamental for modelling internal REC electricity flow and interactions with the wider grid.	Phase to Phase (2021); Bhattacharyya et al. (2008)
Solar PV	Photovoltaic panels for generating renewable electricity.	Yes	Central to renewable energy generation in RECs; widely studied and mature technology.	Awad & Gül (2018); Weckesser et al. (2021)
Transformers	Devices for voltage conversion to avoid overloading the system.	Yes	Critical for managing grid congestion and ensuring compatibility with local transmission systems.	Phase to Phase (2021); Bhattacharyya et al. (2008)
User Demand	Represents different consumer types based on EU and national standards.	Yes	Reflects regulatory frameworks and ensures accurate modelling of diverse urban energy demands.	DIRECTIVE (EU) 2019/944; Rijksoverheid (2024)
Wind Energy	Wind turbines for renewable electricity generation.	No	Urban areas often lack the space and wind conditions necessary for effective deployment of wind energy.	Alabi et al. (2023)

B. Research Flow Diagram

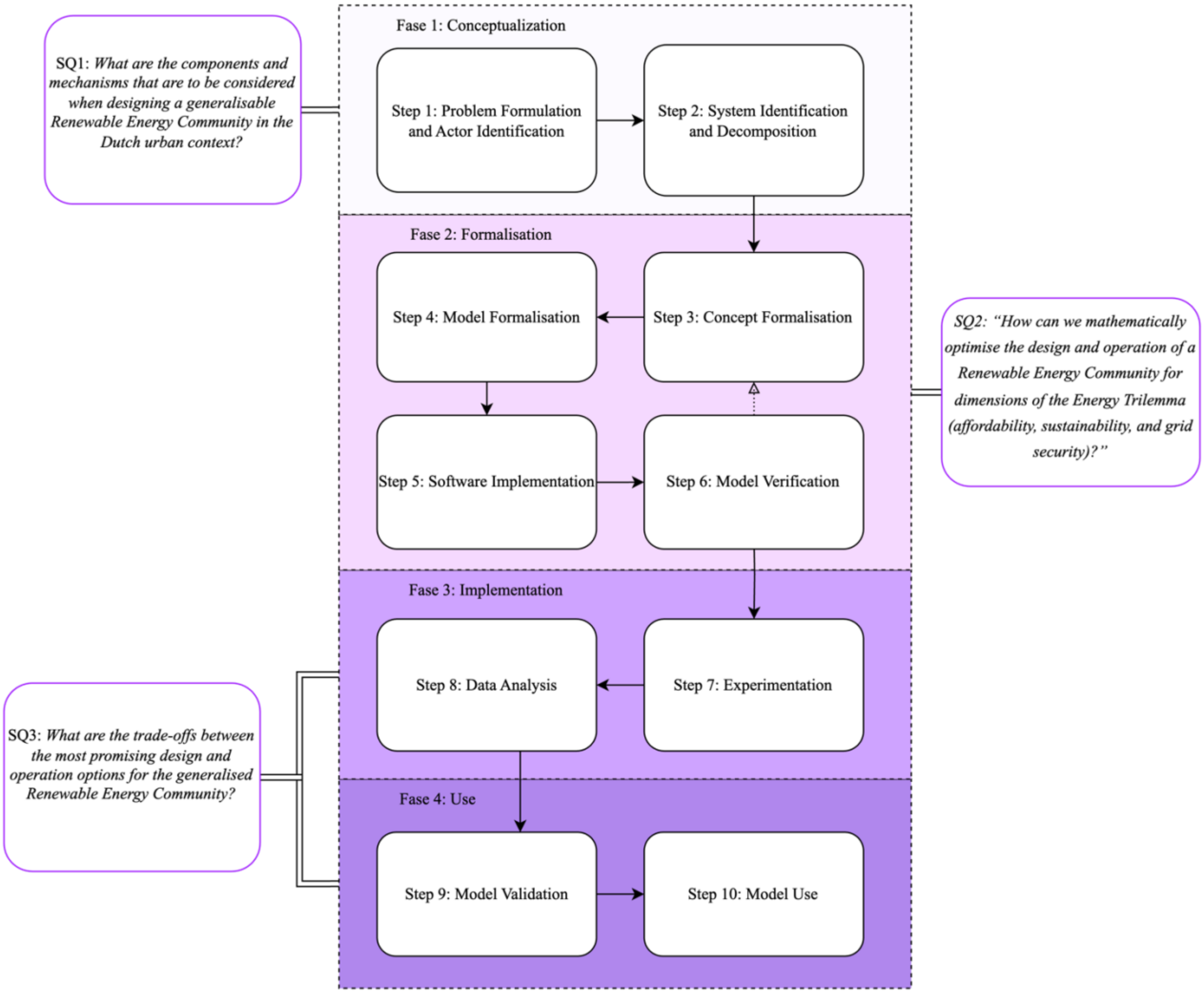

Figure 42: Research Flow Diagram.

C. Model Inputs

Table 6: Model parameters, description, reasoning and source.

Tech	Installed at	Parameter	Value	Description	Reasoning	Source
supply_grid_power	Transformer	Name	Grid import	Name of the technology or component.		
		base_tech	supply	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_out	power_MV	Output energy carrier type for the technology.		
		source_use_max	.inf	Maximum usage capacity of the energy source.	We assume that the grid can supply as much as the transformer is capable of.	
		flow_cap_max	.inf	Maximum flow capacity of the technology.		
		lifetime	25	Expected operational lifespan of the technology in years.		
		cost_flow_out	0.37 kg co2_emissions/ kW	Cost associated with the energy output flow.	We assume a CO_2 equivelant for grid imports as a timeseries is not available to us.	(STATISTA, 2024)
		cost_flow_out	Day-ahead price timeseries [€ /kWh]	Cost associated with the energy output flow.	We assume that prosumers may trade on the spot market if they identify as a renewable energy community.	(ENTSOE, 2024.)
solar_power	Prosumers	name	Solar photovoltaic power	Name of the technology or component.		
		base_tech	supply	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_out	power_pv	Output energy carrier type for the technology.		
		source_unit	per_cap	Capacity factor, determined by the solar availability on the day.	The capacity factor timeseries is taken for Utrecht as it is in the centre of the Netherlands, a national capacity factor was not found	(Pfenninger & Staffell, 2016)
		flow_out_parasitic_eff	0.9	Efficiency of a solar panel to convert solar power into electricity.		Expert judgment
		flow_cap_max	240	Maximum flow capacity of the technology per node.	6 [kW/prosumer] * 40 [prosumer/node] = 240 kW/node	(Rijksoverheid, 2024)
		lifetime	20	Expected operational lifespan of the technology in years.		Expert judgment
		cost_flow_cap	730 € / kW	Cost of one kw of solar panels.		Accenture
unmet_demand	Sink	Name	Unmet demand	Name of the technology or component.	This techs tracks whether the system is able to fulfill demand	
		base_tech	supply	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_out	power	Output energy carrier type for the technology.		
		source_use_max	.inf	Maximum usage capacity of the energy source.	Should enable the system to solve when there is not enough supply	
		flow_cap_max	.inf	Maximum flow capacity of the technology.		
		lifetime	.inf	Expected operational lifespan of the technology in years.		
		cost_flow_out	1.00E+09	Cost associated with the energy output flow.	High costs to make sure it isn't used.	

demand_power	Prosumers	Name	Power demand	Name of the technology or component.		
		base_tech	demand	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power	Input energy carrier type for the technology.		
			e1 profiles * 2500 kWh * 40 prosumers	The demand profile for the nodes that consist of 40 e1 prosumers.	We scale the profile by multiplying each time step by the amount of expected annual electricity demand for the whole node consisting of 40 prosumers	(Bhattacharyya et al., 2008; MFFBAS, 2024; Rijksoverheid, 2024)
			e2 profiles * 5000 kWh * 40 prosumers	The demand profile for the nodes that consist of 40 e2 prosumers.		(Bhattacharyya et al., 2008; MFFBAS, 2024; Rijksoverheid, 2024)
sell_grid_power	Transformer	name	Grid export	Name of the technology or component.		
		base_tech	demand	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power_MV	Input energy carrier type for the technology.		
		flow_cap_max	.inf	Maximum flow capacity of the technology.	We assume that the grid can in-feed as much as the transformer is capable of.	
		cost_flow_in	Day-ahead price timeseries [€ /kWh]	The price of electricity at time *t*.	We assume that prosumers may trade on the spot market if they identify as a renewable energy community.	(ENTSOE, 2024)
curtailment	Prosumers	name	Curtailment	Name of the technology or component.		
		base_tech	demand	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power_pv	Input energy carrier type for the technology.	This is a dummy variable used to measure how much solar power we curtail per year.	
		cost_flow_out	0 €/kWh	Cost associated with the energy output flow.	Shutting down solar panels is free.	
transformer_in	Transformer	name	Transformer in	Name of the technology or component.		
		base_tech	conversion	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power_MV	Input energy carrier type for the technology.		
		carrier_out	power	Output energy carrier type for the technology.		
		flow_in_eff	0.95	Efficiency of the incoming energy flow.		Expert judgment
		flow_out_eff	0.95	Efficiency of the outgoing energy flow.		Expert judgment
		flow_cap_max	400	Maximum flow capacity of the technology.	Transformers are typically scaled to 1.5 kW per household with a 30% margin.	(Bhattacharyya et al., 2008; Phase To Phase, 2021; Weckesser et al., 2021)
		lifetime	25	Expected operational lifespan of the technology in years.		Expert judgment
		cost_flow_cap	Transformer_congestion_factor	A cost conceptualisation associated with consumption congestion.	We have conceptualised a transformer congestion factor based on the day	Concept

			timeseries [dimensionless]		ahead price as granulair congestion data is not available, and too location specific.	
transformer_out	Transformer	name	Transformer out	Name of the technology or component.		
		base_tech	conversion	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power	Input energy carrier type for the technology.		
		carrier_out	power_MV	Output energy carrier type for the technology.		
		flow_in_eff	0.95	Efficiency of the incoming energy flow.		Expert judgment
		flow_out_eff	0.95	Efficiency of the outgoing energy flow.		Expert judgment
		flow_cap_max	400	Maximum flow capacity of the technology.	Transformers are typically scaled to 1.5 kW per household with a 30% margin.	(Bhattacharyya et al., 2008; Phase To Phase, 2021; Weckesser et al., 2021)
			25	Expected operational lifespan of the technology in years.		Expert judgment
		cost_flow_cap	timeseries [dimensionless]	A cost conceptualisation associated with feed-in congestion.	We have conceptualised a transformer congestion factor based on the day ahead price as granulair congestion data is not available, and too location specific.	Concept
pv	Transformer	name	pv	Name of the technology or component.	This is a dummy tech, enabling the measurement of curtailment per year.	
		base_tech	conversion	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power_PV	Input energy carrier type for the technology.		
		carrier_out	power_LV	Output energy carrier type for the technology.		
		flow_in_eff	1	Efficiency of the incoming energy flow.		
		flow_out_eff	1	Efficiency of the outgoing energy flow.		
		flow_cap_max	.inf	Maximum flow capacity of the technology.		
		lifetime	.inf	Expected operational lifespan of the technology in years.		
battery	Prosumers	name	Battery storage LV	Name of the technology or component.		
		base_tech	storage	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power	Input energy carrier type for the technology.		
		carrier_out	power	Output energy carrier type for the technology.		
		flow_cap_max	.inf	Maximum flow capacity of the technology.		
		storage_cap_max	.inf	Maximum storage capacity for the technology.		
		storage_discharge_depth	0.01	There should always remain 1% of charge in the battery.		Expert Judgement
		lifetime	15	Expected operational lifespan of the technology in years.		(Weckesser et al., 2021)
		flow_cap_per_storage_cap_max	0.25	Ratio of flow capacity to storage capacity.		Expert Judgment
		flow_out_eff	0.97	Efficiency of the outgoing energy flow.		(Weckesser et al., 2021)

		flow_in_eff	0.98	Efficiency of the incoming energy flow.		(Weckesser et al., 2021)
		storage_loss	0.01	Percentage of energy loss during storage.		Expert Judgement
		cost_storage_cap	800 € / kW	Cost associated with the storage capacity.		(Secchi et al., 2021; Weckesser et al., 2021)
battery	Prosumers	name	Battery storage MV	Name of the technology or component.	Due to interest from Accenture, we include a MV battery that is placed before the transformer, even though it might not be legally possible.	
		base_tech	storage	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power_MV	Input energy carrier type for the technology.		
		carrier_out	power_MV	Output energy carrier type for the technology.		
		flow_cap_max	.inf	Maximum flow capacity of the technology.		
		storage_cap_max	.inf	Maximum storage capacity for the technology.		
		storage_discharge_depth	0.01	There should always remain 1% of charge in the battery.		Expert Judgement
		lifetime	15	Expected operational lifespan of the technology in years.		(Weckesser et al., 2021)
		flow_cap_per_storage_cap_max	0.25	Ratio of flow capacity to storage capacity.	We assume that a battery takes a maximum of 4 hours to discharge.	Expert Judgment
		flow_out_eff	0.95	Efficiency of the outgoing energy flow.		(Weckesser et al., 2021)
			0.95	Efficiency of the incoming energy flow.		(Weckesser et al., 2021)
		storage_loss	0.01	Percentage of energy loss during storage.		Expert Judgement
		cost_storage_cap	400 € / kW	Cost associated with the storage capacity.		(Secchi et al., 2021; Weckesser et al., 2021)
power_lines		name	Electrical power distribution	Name of the technology or component.		
		base_tech	transmission	Categorization of the technology type (e.g., supply, demand, conversion).		
		carrier_in	power	Input energy carrier type for the technology.		
		carrier_out	power	Output energy carrier type for the technology.		
		flow_cap_max	720 kW	Maximum flow capacity of the technology.	Prosumer power connection cables can carry 3*25A*240V*40 prosumers	(MFFBAS, 2024; Phase To Phase, 2021)

D. Model Results Under Different Assumptions

In this appendix we give context to the assumptions made in the modelling process.

D.1. Weight Distribution

This Appendix explores the impact of using different weight distributions in the multi-objective optimization model. The chosen methodology for weight generation, based on a Dirichlet distribution, was designed to address challenges related to objective magnitudes and provide balanced insights. However, alternative approaches could have led to different results. This section evaluates the implications of assuming alternative weight distributions.

To illustrate the variability of potential scenarios, we first examine the weight distribution under an alternative assumption. Unlike the Dirichlet distribution used in the thesis, this alternative approach represents a more uniform sampling of the weight space. Figure 43 showcases the resulting distribution. While this method increases representation of extreme weight combinations, it lacks the smoothing effect provided by Dirichlet sampling, which better reflects balanced and relevant scenarios.

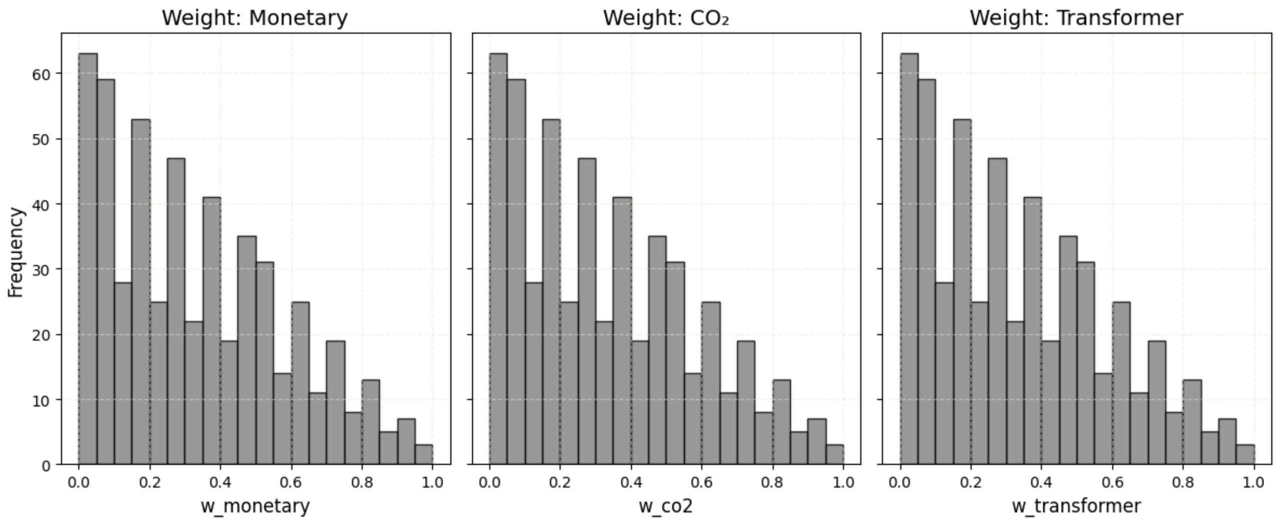

Figure 43: Uniform distribution of weights.

Figure 44 demonstrates the raw Pareto front results generated using the alternative weight distribution. Without filtering, the model produces highly extreme scenarios. These include configurations with unrealistic outcomes, such as very high monetary costs or severe transformer congestion, driven by the overemphasis on specific objectives. Additionally, variables like unmet demand, which were controlled in the thesis model, are more prominent here, further skewing the solution space.

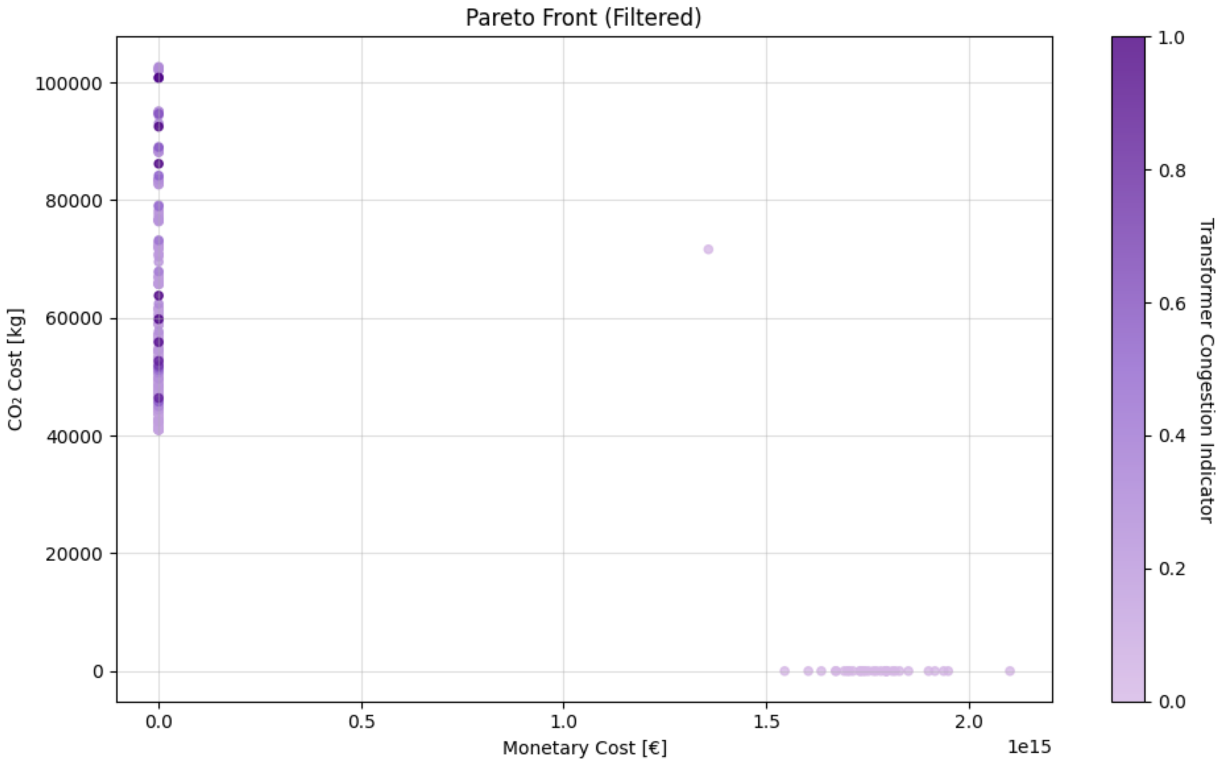

Figure 44: Unfiltered Pareto front from the uniform weight distribution.

To address these extremes, we applied filtering to exclude unrealistic or irrelevant scenarios, as shown in Figure 45. The filtered results present a larger solution space compared to the thesis analysis. While this broader range includes more extreme cases, it lacks the nuanced insights provided by the analysis in the main results. Instead, the filtered space emphasizes a higher number of edge cases, which are less relevant for exploring practical trade-offs in Renewable Energy Communities (RECs).

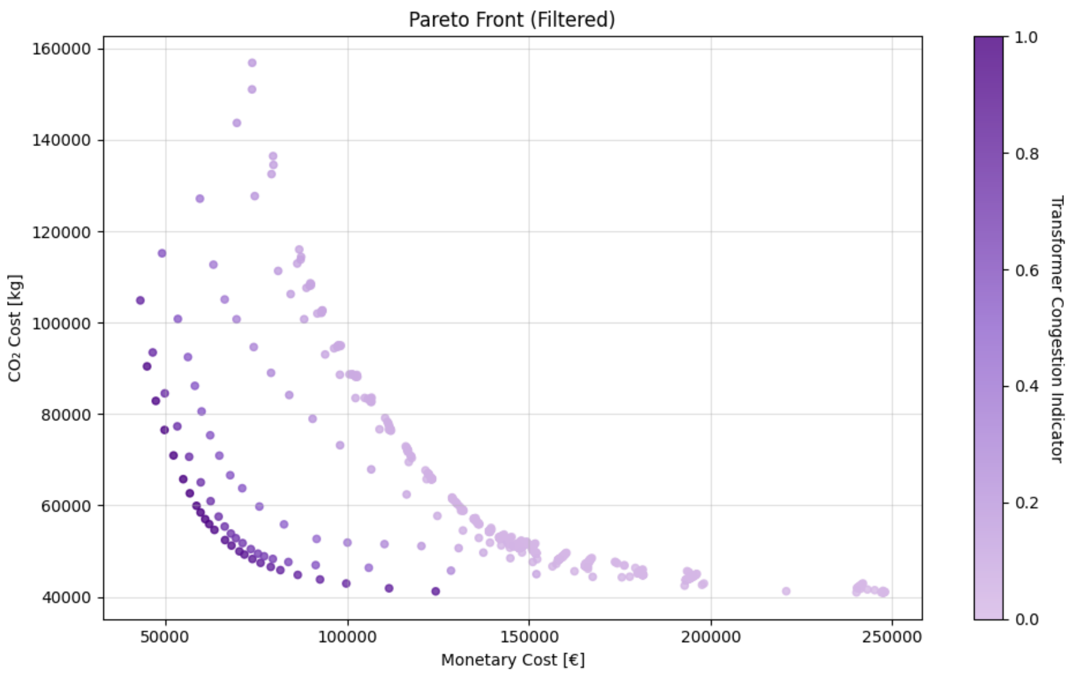

Figure 45: Filtered Pareto front from the uniform distribution.

The choice of a Dirichlet distribution for generating weight distributions introduced a trade-off between the exploration of balanced versus extreme scenarios. While alternative distributions could provide a broader solution space, they risk producing results that are less actionable or meaningful for stakeholders. The filtered results shown here illustrate that while extremes are identifiable, they provide limited value for analysing realistic REC designs. Future work could explore hybrid approaches to weight generation that balance representational diversity with relevance to practical applications.

D.2. Clustering

In this section, we evaluate an alternative clustering approach based on the design, and operational decision variables. Here, we use flow cap for the design variables and flow in/out for the operational variables to identify distinct design and operation clusters. While this method could offer valuable insights into the system's behaviour, we decided not to use it in the main analysis due to its reduced interpretability and limited alignment with the energy trilemma framework. Although the resulting clusters are similar to those used in the main text, they emphasize extreme design and operational strategies rather than balanced trade-offs, which could be another good strategy for further analysis of the results.

To assess the optimal number of clusters, we calculated the elbow and silhouette scores for this alternative clustering approach, shown in Figures 46 and 47. The elbow method suggests that four clusters capture sufficient variation in the data, while the silhouette score confirms that three clusters maximize separation and cohesion.

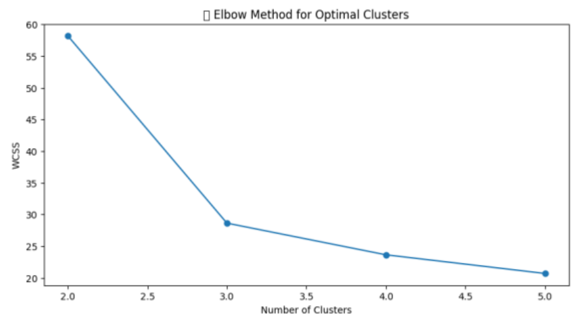

Figure 46: Elbow Method for alternative cluster approach.

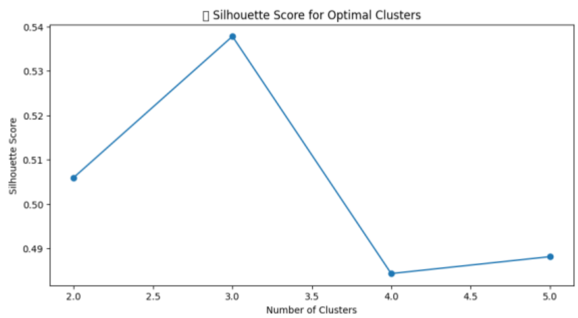

Figure 47: Silhouette Score for alternative cluster approach.

Figures 48 and 49 present the Pareto front results for three and four clusters, respectively, under the alternative clustering approach. Similar to the main analysis, the resulting clusters represent distinct solution spaces across the Pareto front. However, instead of clearly aligning with the energy trilemma dimensions (affordability, sustainability, and grid security), these clusters highlight extreme design and operational strategies.

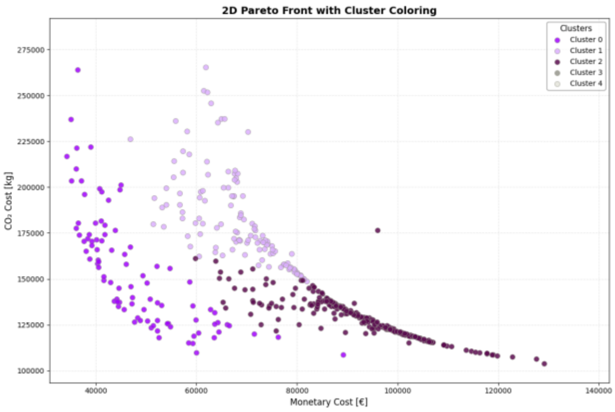

Figure 48: Three clusters for alternative cluster approach.

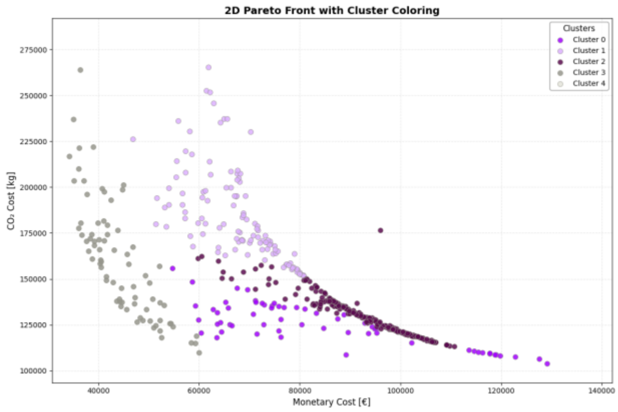

Figure 49: Four clusters for alternative cluster approach.

The clusters derived from this alternative method are similar, but less intuitive and do not align neatly with the energy trilemma framework, making it harder to draw meaningful conclusions about trade-offs between monetary costs, CO_2 emissions, and transformer congestion. In contrast, the main clustering approach ensures that the scenarios are directly interpretable within the trilemma dimensions, facilitating a clearer and more structured analysis. The alternative clustering results, while valid, are presented here to demonstrate the trade-offs inherent in methodological choices and highlight the rationale behind our selected approach.

E. Flow Diagrams of the PV and MV Power Levels

Figure 50: Operational plots for the PV Power level.

Figure 51: Operational plots for the MW Power level.

F. Sensitivity Analysis of the Parameters

Table 7: Sensitivity analysis of the parameters.

Component	Parameter	Uncertainty	Sensitivity	Reasoning
Supply Grid Power	Flow capacity	Medium	High	Reflects the grid's ability to supply electricity; influenced by transformer size and market conditions.
	Grid power costs and revenues	High	High	Driven by fluctuating market prices and prosumer contracts.
	Lifetime	Low	Low	Assumes standard grid component longevity.
Solar Power	Maximum capacity of installable PV	High	High	Urban constraints and roof availability create variability in potential installations.
	Efficiency (Inverter Losses)	Low	Medium	Technology-dependent; incremental efficiency gains possible.
	Capacity Factor	High	Low	Solar radiance is relatively stable year-over-year, reducing its sensitivity.
	Price	High	High	Expected to decrease over time, significantly impacting system design.
Unmet Demand	Cost of unmet demand	Low	High	Models extreme penalties for unmet demand to ensure system feasibility.
Demand Power	Electricity demand	High	High	Future electrification (e.g., EVs, heat pumps) increases uncertainty.
Sell Grid Power	Flow capacity	Medium	High	Assumes grid can export as much as transformer allows.
Transformer In/Out	Transformer size	High	High	Critical for managing congestion; infrastructure-dependent.
	Efficiency	Low	Medium	Influenced by transformer technology and maintenance.
Battery (LV & MV)	Price	High	High	Expected to decrease over time, significantly impacting system design.
		Medium	Medium	Impacts operational performance and cost-effectiveness.
	Lifetime	Medium	Medium	Real-world performance depends on charge cycles and environmental conditions.
	Storage capacity	Medium	Medium	Determines flexibility and load-balancing capabilities.

Power Lines	Transmission line capacity	Medium	Low	Urban infrastructure is often over-dimensioned to handle peak loads.
	Transmission efficiency	Low	Medium	Energy losses during distribution can affect flexibility and costs.
Weights	Objective prioritization	High	High	Critical for balancing energy trilemma dimensions (cost, sustainability, security) and driving extreme scenario outcomes.
Node Distribution	Prosumers (e1, e2 configurations)	Medium	Medium	Spatial and geographical distribution impacts energy flow and optimization results.
Solver Parameters	Tolerances (feasibility/optimality)	Low	Medium	Small adjustments in solver precision can affect results.
Time Horizon	Temporal granularity	Medium	High	Seasonal or annual data subsets influence operational insights but less so for general trends. Furthermore, forecasting is limited due to restricted data availability.

G. Changes Applied for the One at a Time Sensitivity Analysis

Table 8: Parameter change range and reasoning for the structural sensitivity analysis.

Category	Scenario Name	Parameter Change	Reasoning
Solar Power Capacity	Zero PV Capacity	Max flow capacity set to 0	Represents no solar generation
	120 kW	Max flow capacity set to 120 kW	Limited solar generation capacity
	400 kW	Max flow capacity set to 400 kW	Increased renewable integration
	Infinite Capacity	Unlimited PV capacity (inf)	Maximal renewable integration potential
LV Battery Capacity	Zero Capacity	Max flow capacity set to 0	Represents no batteries
	120 kW	Max flow capacity set to 120 kW	Limited battery capacity
	400 kW	Minimal flow capacity set to 400 kW	Increased battery
	600 kW	Minimal flow capacity set to 600 kW	Forcing the model
	800 kW	Minimal flow capacity set to 800 kW	Forcing the model
MV Battery Capacity	Zero Capacity	Max flow capacity set to 0	Represents no batteries
	120 kW	Max flow capacity set to 120 kW	Limited battery capacity
	400 kW	Minimal flow capacity set to 400 kW	Increased battery
	600 kW	Minimal flow capacity set to 600 kW	Forcing the model
	800 kW	Minimal flow capacity set to 800 kW	Forcing the model

Table 9 Parameter change range and reasoning for the parameter sensitivity analysis.

Category	Scenario Name	Parameter Change	Reasoning
Objective Weights	Affordable Extreme	[0.98, 0.01, 0.01]	Prioritizes cost minimization
	Sustainable Extreme	[0.01, 0.98, 0.01]	Emphasizes reduced CO2 emissions
	Secure Extreme	[0.01, 0.01, 0.98]	Minimises transformer congestion
Grid prices		Buy 0.28, Sell Day-ahead	Retail buy price, sell at spot market
		Buy Day-ahead, Sell 0.03	Buy at spot, sell retail price low

		Buy Day-ahead, Sell 0.13	Buy at spot, sell retail price high
		Buy 0.28, Sell 0.13	Higher sell price boosts revenue
		Buy 0.28, Sell 0.03	Lower sell price reduces revenue potential
		Buy 0.28, Sell 0.28	Balanced buy-sell grid prices
Transformer Size	1 kW	Max flow capacity limited to 1 kW	Represents extremely undersized capacity
	200 kW	Max flow capacity limited to 200 kW	Restricts grid flexibility
	800 kW	Max flow capacity limited to 800 kW	Excess capacity, potential underutilization
	1200 kW	Max flow capacity limited to 1200 kW	Represents oversized grid capacity
Demand Sensitivity	Low Electrification	Demand reduced by 50%	Reflects minimal electrification adoption
		Demand increased by 200%	Aggressive electrification scenario
Battery Price	$500/kWh	Storage cost set to $500	Represents mid-range cost assumption
	$250/kWh	Storage cost set to $250	Lower cost encourages wider adoption
	$100/kWh	Storage cost set to $100	Very low cost drives significant adoption
	$1/kWh	Storage cost set to $1	Near-zero storage cost scenario
Solar Power Price	$1200/kWh	Solar Power cost set to $1200	Highest price identified in the literature
	$1000/kWh	Solar Power cost set to $1000	High price
	$800/kWh	Solar Power cost set to $800	Base price
	$600/kWh	Solar Power cost set to $600	Lowest price identified in the literature
	$400/kWh	Solar Power cost set to $400	Hypothetical price

H. Project Planning

Table 10: Overview of Project Events (23 Weeks).

Project Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Events	S				KO							Mid-Term					Break		GL		Final-Doc		D

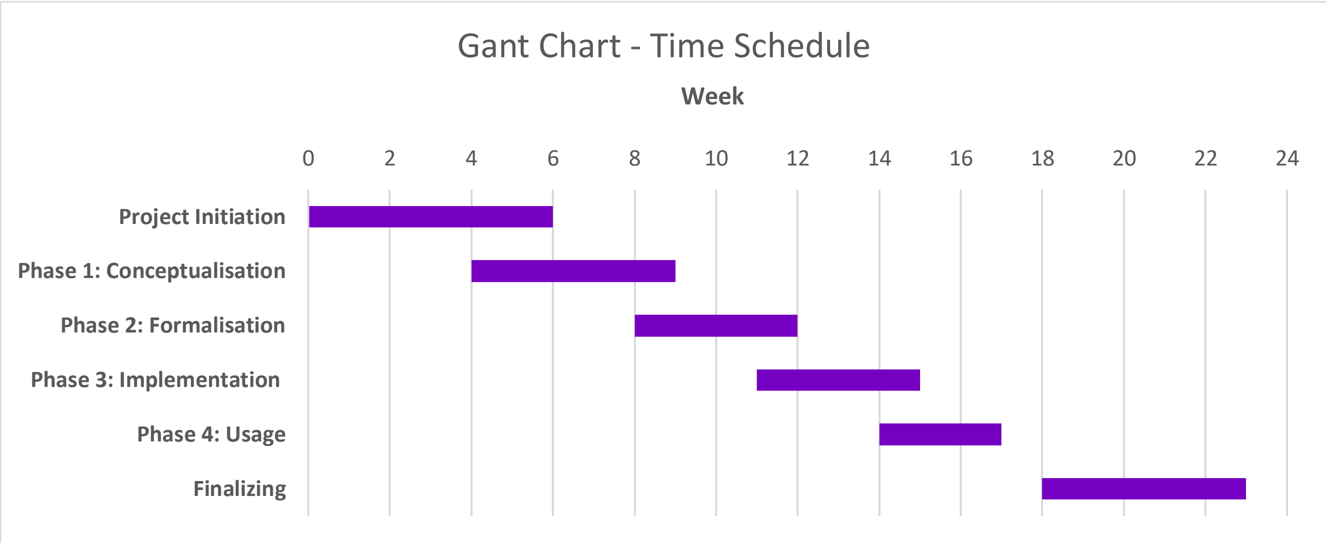

Figure 52: Research planning.